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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Nondestructive Examination Techniques II, contains six modules: Fundamentals of Ultrasonic Testing, Operating of Ultrasonic Test Equipment, Fundamentals of Magnetic Particle Testing, Operation of Magnetic Particle Test Equipment, Fundamentals of Eddy Current Testing, and Operation of Eddy Current Test Equipment. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guides are also available--see CE 026 856 and CE 026 639-643.) (LRA)

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ED192114

Nuclear Technology Series

COURSE 32

NONDESTRUCTIVE EXAMINATION

(NDE) TECHINQUES II

CENTER FOR OCCUPATIONAL RESEARCH
AND DEVELOPMENT, INC.
4800 LAKEWOOD DRIVE
WACO, TEXAS 76710

JUN 1980

CE 026 674

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PREFACE

ABOUT NUCLEAR TECHNOLOGY MODULES

The modules - developed by TERC-SW for use in two-year postsecondary technical institutions to prepare technicians for employment - are useful in industry for updating employees in company-sponsored training, and as laboratory texts in engineering schools. The principles, techniques and skills taught in the modules, based on tasks that nuclear technicians perform, were obtained from a nationwide advisory committee of employers of nuclear technicians. Each module was written by a working technical expert/experienced writer team and tested with students.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Module Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify and define, rather than words with many interpretations, such as know, understand, learn and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Materials, which identify the equipment required to complete the laboratory procedure.

Procedures, which is the experiment section, or "hands-on" portion of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

Reference Materials, which are included as suggestions for supplementary reading/viewing for the student.

Test, which measures the student's achievement of the prestated objectives.

CONTENTS

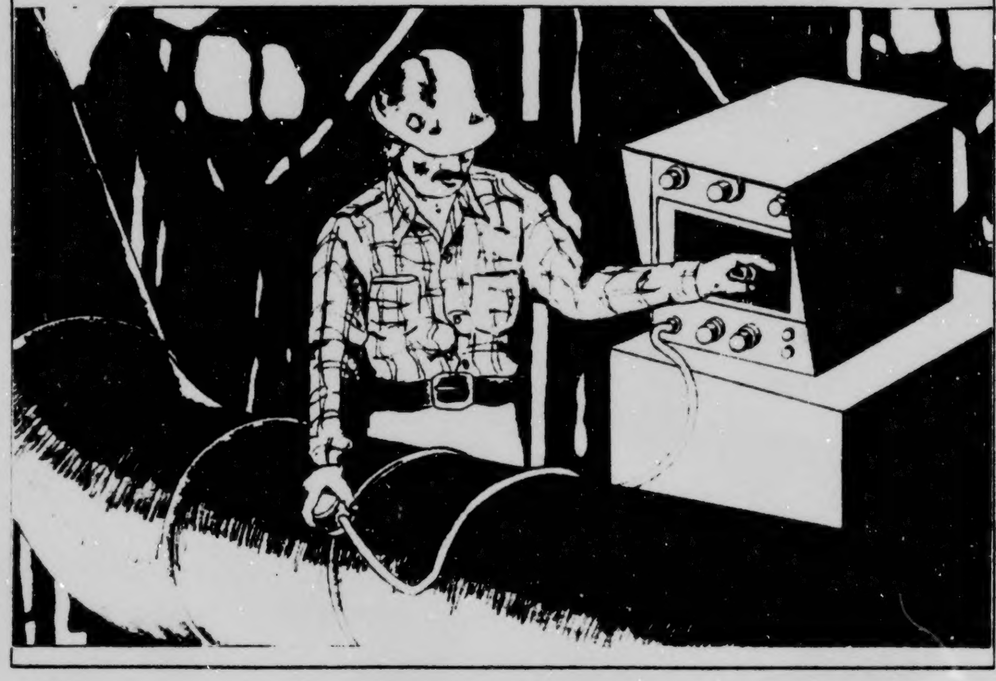
Preface

Module 32-1 Fundamentals of Ultrasonic Testing
Module 32-3 Operation of Ultrasonic Test Equipment
Module 32-3 Fundamentals of Magnetic Particle Testing
Module 32-4 Operation of Magnetic Particle Test Equipment
Module 32-5 Fundamentals of Eddy Current Testing
Module 32-6 Operation of Eddy Current Test Equipment

NUCLEAR TECHNOLOGY

MODULE 32 - 1

FUNDAMENTALS OF ULTRASONIC TESTING



COURSE 32: NONDESTRUCTIVE EXAMINATION (NDE)

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

MODULE 32-1	Fundamentals of Ultrasonic Testing
MODULE 32-2	Operation of Ultrasonic Test Equipment
MODULE 32-3	Fundamentals of Magnetic Particle Testing
MODULE 32-4	Operation of Magnetic Particle Test Equipment
MODULE 32-5	Fundamentals of Eddy Current Testing
MODULE 32-6	Operation of Eddy Current Test Equipment

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INTRODUCTION

The Nuclear QA/QC Technician may qualify as an ultrasonic test inspector or may have responsibility for reviewing ultrasonic inspection reports. In these capacities, the technician must be familiar with theory, equipment, test techniques, and acceptance criteria associated with ultrasonic inspection.

Ultrasonic Testing is a nondestructive technique for the examination of materials and products utilizing the transmission of high frequency sound waves, also known as ultrasound, in the test material. This is in contrast to radiographic inspection which uses either x-rays or gamma rays. Both ultrasonic testing and radiography are volumetric inspection methods. That is, the entire volume of material can be examined with these methods.

This module introduces the student/trainee to the basic behavior of ultrasound, describes ultrasonic test equipment, and outlines the principal methods of ultrasonic testing. The immediate purpose of this module is to prepare the student/trainee for the second ultrasonic module which details specific testing techniques (Module 32-2, Course 32). This module and Module 32-2 are intended to prepare the student/trainee for the American Society for Nondestructive Testing's Level II Certification Test for Ultrasonic Testing.

MODULE PREREQUISITES

Course 26, Nondestructive Examination Techniques I should have been completed before proceeding to this course.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Define the following terms:
   - wavelength
   - period
   - frequency
   - velocity
   - acoustic impedance
   - reflection
   - refraction
   - longitudinal wave
   - transverse wave
   - surface wave
2. Identify and describe the following components and their functions for a typical ultrasonic test setup: probe, signal generator, receiver, cathode ray tube, amplifier, clock, and power supply.
3. Identify the type and purpose of an ultrasonic test given a schematic diagram of the test setup.
4. Identify, and briefly describe, the test method which would accomplish a stated test requirement.
5. Name the four (4) basic wave modes discussed in this module and describe each.
6. Name the four (4) classes of ultrasonic test and describe each.
7. Name the three (3) types of pulse-echo test and distinguish between them.

NOTES TO INSTRUCTOR/STUDENT

This module introduces the student/trainee to the basic behavior of ultrasound, describes ultrasonic test equipment, and outlines the principal methods of ultrasonic testing. This material is intended to prepare the student/trainee for the American Society for Nondestructive Listings Level II Certification Test for Ultrasonic Testing.

Every attempt has been made in preparing this module to deal with the principles of ultrasound so that the student/trainee with a moderate knowledge of physics and mathematics can understand this important nondestructive examination technique. Although there are no stated prerequisites for this module, a brief review of electronic principles along with fundamentals of trigonometry may be useful for better understanding of this material.

PRINCIPLES OF ULTRASONIC WAVE BEHAVIOR

Oscillations and Waves

The ultrasonic testing of materials makes use of mechanical vibrations or oscillations of the atoms in matter to conduct the tests. These oscillations travel as waves and by measuring and analyzing the behavior of the waves in the test material, much can be learned about the structure of the material.

To understand ultrasonic testing, therefore, we should first look at waves. What are waves? It is best, perhaps, to first look at examples of waves. Consider what happens when a small stone is dropped into a smooth pond. A circular pattern spreads out from the point at which the stone hit the water. Such a moving disturbance is a wave. It is important to realize that what is actually moving is the disturbance, and not the water itself. This can be clearly seen if you watch something floating in the water, such as a small chip of wood or a fishing line float. The chip or float merely moves up and down or oscillates vertically as the wave passes; it does not move horizontally with the wave. The wave, or disturbance has travelled through the water, but the water itself has not moved with the wave.

A second example of how a wave moves in a material is the rippling of a flag in the breeze. The rippling of the flag is actually the travelling of waves along its length. Obviously, the individual points on the flag remain fixed with respect to each other as the ripples move along the flag's length. The stripes on the American flag don't get longer or shorter and the stars don't move around on the field. Just as the water in the pond does not move with the wave, the cloth of the flag is the same as before and after passage of the wave.

The travelling of a wave is referred to as propagation. When water travels outwardly, it is common to say that it propagates outwardly. Similarly, reference to the travel of a sound wave is by stating the direction of propagation.

The speed with which a wave travels in its direction of propagation is its velocity.

Waves can be either periodic or non-periodic. A periodic wave is one in which the motion of the material repeats itself over and over in a regular pattern over time. A non-periodic wave is one in which the repetition is not regular or there is no repetition at all. A very important type of periodic wave is the very short burst of periodic waves called a pulse. Hereafter, unless stated otherwise, wave means periodic wave.

Wave Parameters

There are three basic parameters of a wave that must be defined and related to each other: wavelength, velocity, and frequency. The parts of a wave are first reviewed to permit definition of these parameters.

For a surface wave, such as the pond waves and illustrated in Figure 32-1-1, the highest point of the wave is the crest. The lowest point is the trough. The vertical distance from the equilibrium position to the crest or the trough (those distances are equal) is the amplitude of the wave. The cycle of a wave is one complete "turn" of the wave, from crest to crest, for example.

The distance between successive crests or troughs or other corresponding points in a wave is defined as the wavelength, which is usually referred to by the Greek letter lambda (λ). The time it takes a length of a propagating wave equal to one wavelength (1λ) to pass a given point in space is defined as the period, which is frequently referred to by the letter T, although the Greek letter tau (τ) is sometimes used. The number of wavelengths (or crests, or troughs) passing a given point per unit time is defined as the frequency, which is frequently referred to by the letter f, although the Greek letter nu (ν) is sometimes used.

Since frequency is cycles per unit time and period is time per cycle, each is the reciprocal of the other:

$$f = \frac{1}{T} \qquad \text{Equation 32-1-1}$$

Where:

f = frequency

T = period

For ultrasonic testing, frequency is the preferred way to describe how rapidly a wave oscillates and the most common units used are megacycles per second or megahertz (1 Hertz $\equiv$ 1 cycle per second). The abbreviation for megahertz is MHz.

If wavelength is divided by period, the quotient is length divided by time which is velocity, referred to by a lower case c; but more frequently, v outside of ultrasonic testing.

$$c = \frac{\lambda}{T} \qquad \text{Equation 32-1-2}$$

Where:

c = velocity

λ = wavelength

T = period

But Since:

$$f = \frac{1}{T}$$

Then:

$c = \lambda f$ Equation 32-1-3

Where:

c = velocity
λ = wavelength
f = frequency

EXAMPLE

Problem: Find the wavelength of an ultrasonic pulse in steel.

Given: The wave has a frequency of 2.0 MHz and is propagating at 5900 m/sec.

Solution:

$$\lambda = \frac{c}{f} = \frac{5.9\ (10)^3\ \frac{m}{sec}}{2.0\ (10)^6\ \frac{1}{sec}}$$ (Variation of Equation 32-1-3)

$$\lambda = 2.95\ (10)^{-3} m$$

or $\lambda = 2.95$ mm

Notice in the foregoing example that wavelength is inversely proportional to frequency. As frequency increases, wavelength decreases. Because wavelength is important to the interaction of sound and materials, wavelength can be tailored by adjusting frequency to obtain optimum results in ultrasonic testing.

Wave Modes

There are three basic kinds or modes of waves: longitudinal, transverse, and torsional, but only longitudinal and transverse are discussed here. A transverse wave is a wave whose oscillations are perpendicular to its direction of propagation. Examples of transverse waves include water surface waves, guitar strings, and light.

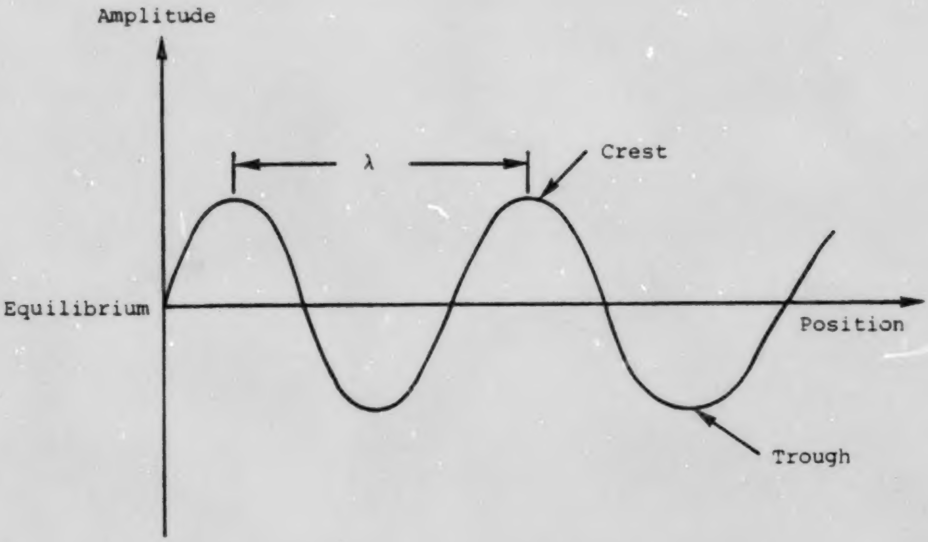

Amplitude
λ
Crest
Equilibrium
Position
Trough

Figure 32-1-1. Surface Wave

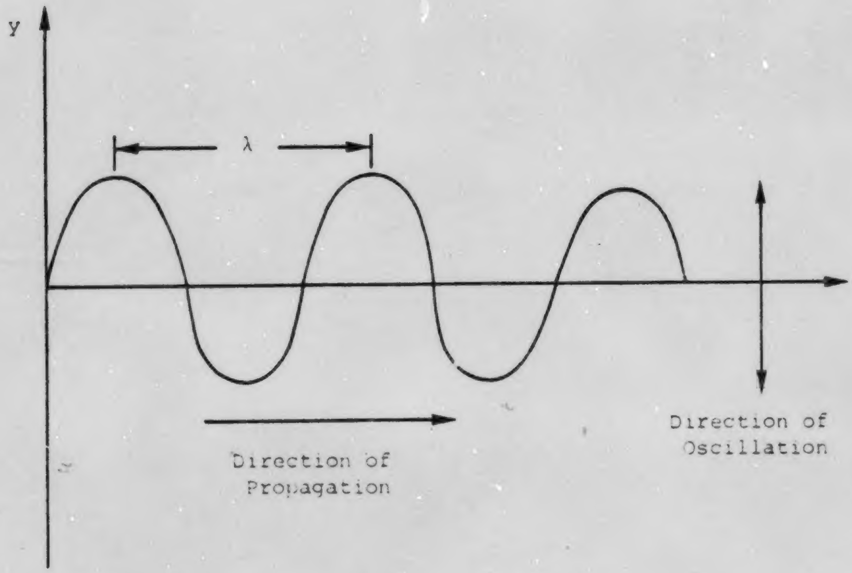

y
λ
Direction of Propagation
Direction of Oscillation

Figure 32-1-2. Transverse Wave

14

A transverse wave is shown schematically in Figure 32-1-2. In ultrasonic testing, transverse waves are quite frequently referred to as shear waves, because the generating mechanism exerts a periodical shear force on the material.

A longitudinal wave is a wave whose oscillations are parallel to its direction of propagation. Examples of longitudinal waves include sound waves in gases and liquids and the rippling of grain stalks by the wind as referred to in "...amber waves of grain...". A longitudinal wave is shown schematically in Figure 32-1-3 below.

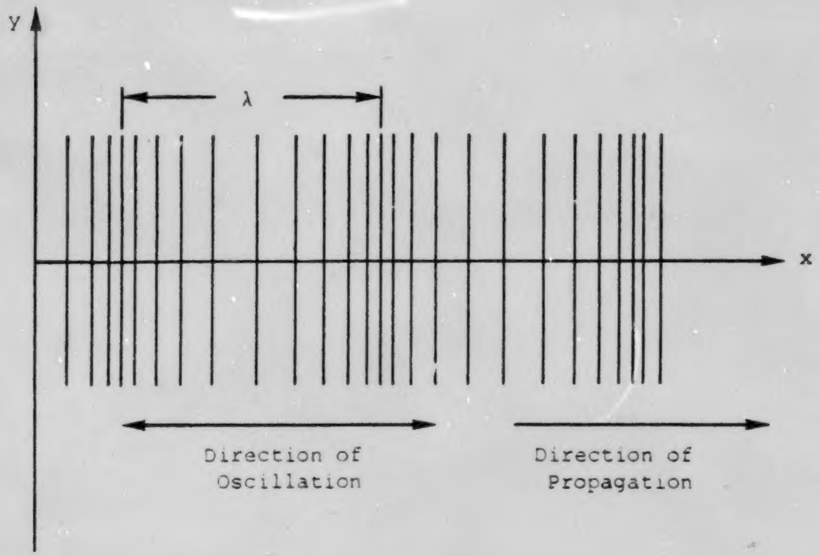


Figure 32-1-3. Longitudinal Wave

Two other classes of waves are important in ultrasonic testing: surface waves and plate waves. What is different is that up until now, only waves in an infinite medium have been considered. Surface and plate waves are merely special cases where the basic transverse mode acts at or near boundries.

The surface or Rayleigh wave propagates on the boundary surface of a metal interfacing with a gas, if the metal is relatively thick. Relatively thick means significantly larger than one wavelength, as that is typically the depth at which particles are only slightly excited by the wave. Figure 32-1-4 illustrates the motion of the top layer of particles in a metal that is undergoing surface wave deformation. As can be seen, this deformation is not sinusoidal.

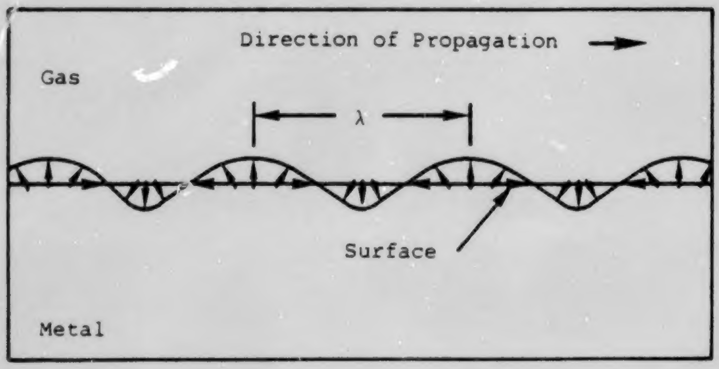


Figure 32-1-4. Surface or Rayleigh Wave

Surface waves propagate along the flat or curved surfaces of a metal at a velocity equal to approximately 90% of a transverse wave in the interior of the same material. Upon hitting a discontinuity in a surface, such as sharp corners, the surface wave is reflected. Thus, ultrasonic surface waves can be used to test very complex surfaces quite simply.

If the metal is not significantly thicker than one wavelength of a surface wave on that material, then the entire plate can oscillate in any of several modes. The two types important in ultrasonic testing are known as Lamb waves. The schematic representations in Figure 32-1-5 illustrate the two basic forms of Lamb wave. Limited use of Lamb waves is used in ultrasonic testing as compared to transverse, longitudinal, and surface waves.

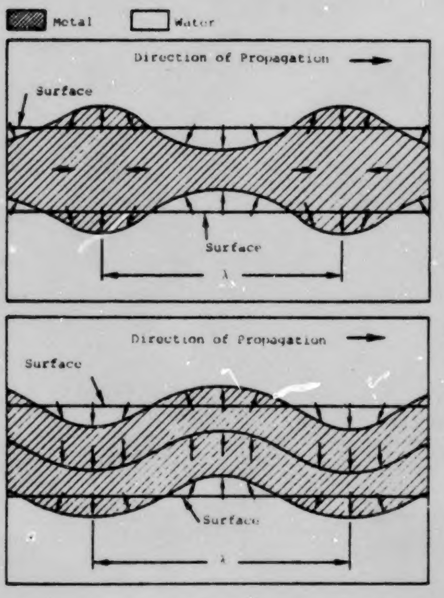


Figure 32-1-5. Plate or Lamb Waves

Sound and Ultrasound

Sound and ultrasound are both oscillations in a material. The only difference is that ordinary or audible sound has a frequency below 20 kHz (20,000 Hz), which is the upper threshold of human hearing, and ultrasound has a frequency above 20 kHz. The ultrasound used in materials testing usually is far higher in frequency than this somewhat arbitrary value of 20 kHz. In fact, its frequency is usually between 200 kHz and 16 MHz.

In referring to oscillations in a material, what is actually oscillating? Since ultrasonic testing described herein is concerned with testing of solids, only solids are closely examined. The structure of a solid can be fairly accurately modelled by imagining it to be composed of small particles, called atoms or ions, held together by springs. (See Figure 32-1-6. The spring connections allow the atoms to move about their equilibrium positions but constrains them from moving too far out of position. If an impulse is provided to one particle, it moves, exerting forces on the particles around it. These other particles then move, and in turn, exert forces on the particles around them, thus causing the initial disturbance to propagate as a wave. Of course, the springs only represent the elastic bonds between the atoms.

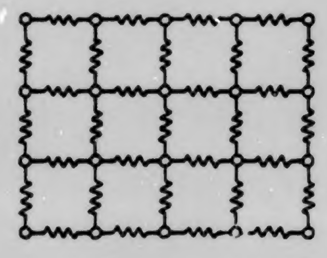


Figure 32-1-6. Model of a Solid

If the particles along a plane in a material are caused to move vertically to the plane, their connections to the adjacent plane of particles cause the second plane to move also. The second plane in turn causes the third to move which causes the fourth to move, and so on. Such oscillation is in the direction of propagation which makes this a longitudinal wave. Because of the pressing together of the planes of atoms, this is also known as a pressure or a compressional wave. In Figure 32-1-7, a longitudinal wave in matter is depicted. The "crests" are those places where the atoms are most tightly packed and the "troughs" are those places where the atoms are least tightly packed.

The speed of the longitudinal wave in matter is referred to as the velocity of sound of the longitudinal wave, written as C_ℓ. This velocity is a material dependent parameter, that is, it changes with the material, but is essentially constant within a given homogeneous material. For selected materials important to the ultrasonic test procedures in the nuclear industry, the velocities of sound of the longitudinal wave are as listed in Table 32-1-1.

Table 32-1-1. Longitudinal Sonic Velocities

Steel	$C_\ell = 5900$ m/sec
Aluminum	$C_\ell = 6300$ m/sec
Water	$C_\ell = 1480$ m/sec

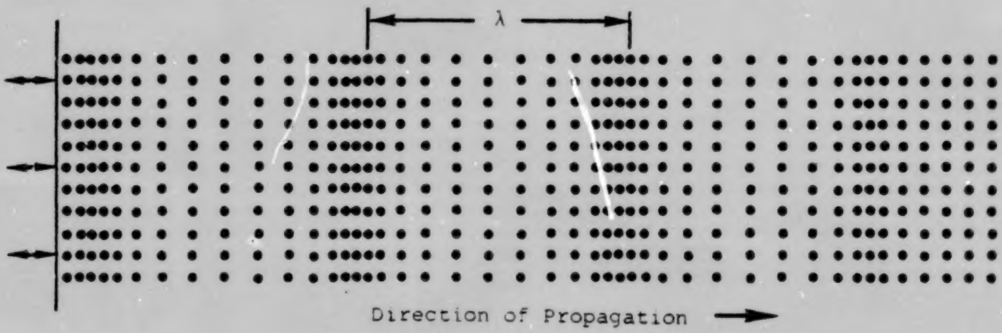


Figure 32-1-7. Longitudinal Wave in a Solid

Because of the values of sound velocities in steel and aluminum, it is convenient to state wavelengths in mm, frequency in MHz, and velocity in km/sec. The convenience of this approach is apparent in the following example

EXAMPLE

Problem: Find the wavelength of a longitudinal wave in steel and aluminum.

Given: Frequency in steel is 1MHz and in aluminum is 5MHz.

Solution:

(a) Steel: $$\lambda_{St} = \frac{C_\ell}{f} = \frac{5.9 \text{ km/sec}}{1.0 \text{ MHz}} = 5.9 \text{ mm}$$

(b) Aluminum: $$\lambda_{Al} = \frac{C_\ell}{f} = \frac{6.2 \text{ km/sec}}{5 \text{ MHz}} = 1.2 \text{ mm}$$

If the particles along a plane in a material are caused to move parallel to the plane, the resulting wave is a transverse wave. In Figure 32-1-8, a transverse wave in solid matter is depicted. Since shearing forces can not be transmitted in a gas or a liquid, transverse waves are only possible in a solid.

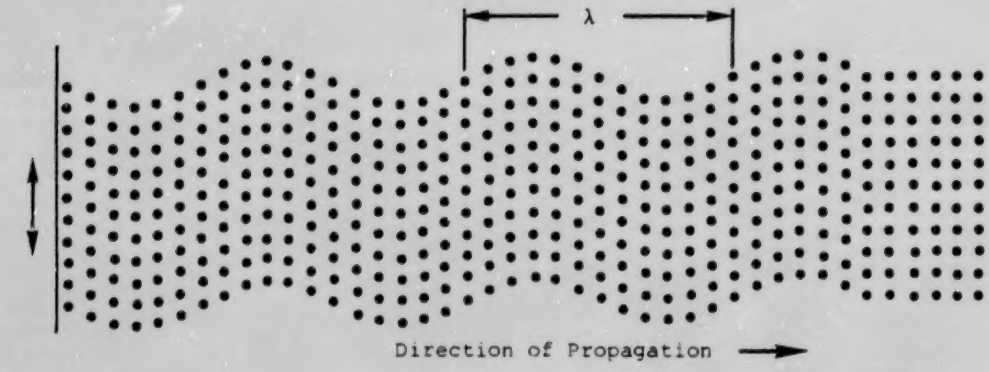


Figure 32-1-8. Transverse Wave in a Solid

The speed of the transverse wave in a solid material is referred to as the velocity of sound of the transverse wave. The transverse velocities of sound in materials of interest are listed in Table 32-1-2.

Table 32-1-2. Transverse Sonic Velocities

Material	Velocity
Steel:	C_t = 3230 m/sec
Aluminum:	C_t = 3130 m/sec
Water:	None

EXAMPLE

Problem: Find the wavelength of a transverse wave in steel and in aluminum.

Given: Frequency in steel is 1MHz and in aluminum is 5MHz.

Solution:

(a) Steel $\lambda_{st} = \frac{C_t}{f} = \frac{3.23 \text{ km/sec}}{1.00 \text{ MHz}} = 3.23 \text{ mm}$

(b) Aluminum $\lambda_{al} = \frac{C_t}{f} = \frac{3.13 \text{ km/sec}}{5.00 \text{ MHz}} = 0.62\text{mm}$

Reflection and Refraction

When waves strike a surface or interface between materials, they are either reflected or transmitted, or both. Reflection occurs when propagating waves hit a smooth flat surface and some or all of the incident (incoming) wave is reflected. The percentage reflected depends upon the nature of the materials and the angle between the wave and the surface. The angle of incidence is measured between the perpendicular to the wave front, hereinafter called the ray, and the perpendicular to the surface, hereinafter called the normal. The angle of reflection is measured between the normal and the perpendicular to the reflected wave front.

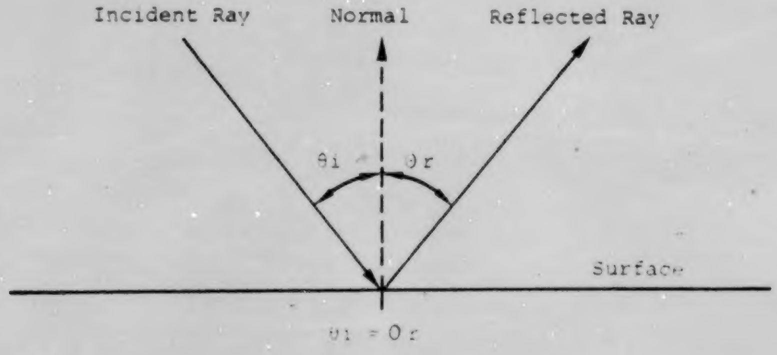


Figure 32-1-9. Reflection

$$\Theta_i = \Theta_r$$ Equation 32-1-4

Where:

Θ_i = Angle of incidence

Θ_r = Angle of reflection

When a ray hits an interface between materials, some of it may be transmitted. The transmitted portion will usually bend, or travel in a different direction in the second material. This process of bending is refraction and the amount of bending is related to the ratio of velocities in the materials.

Snell's Law permits calculation of angle of refraction by Equation 32-1-5. The applicable form of Snell's Law is slightly different than its original form which is used in optics. The reason for the difference is that in ultrasonics there is no "ultimate" wave velocity comparable to the speed of light in a vacuum for optics.

$$\frac{\sin \Theta_i}{\sin \Theta_R} = \frac{C_1}{C_2}$$ Equation 32-1-5

Where:

Θ_i = Angle of incidence

Θ_R = Angle of refraction

C_1 = Sound velocity in medium 1

C_2 = Sound velocity in medium 2

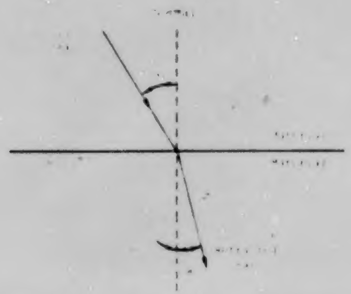


Figure 32-1-10 Refraction

There are several consequences of Snell's Law that are of great importance to ultrasonic testing. First, because longitudinal and transverse waves propagate at different angles. Second, when a wave is incident upon a surface from a normal direction (i.e., $\Theta_i = 0^\circ$), the transmitted ray is undeviated from the incident ray (i.e., $\Theta_R = 0^\circ$) Third, when an incident longitudinal wave is refracted upon entry into the second material, the incident ray is split into a longitudinal wave (L-wave) and a transverse wave (S-wave). (See Figure 32-1-11.)
Fourth, there are certain critical angles beyond which waves are completely reflected when passing into a medium where the velocity of sound is higher. (See Figure 32-1-12)

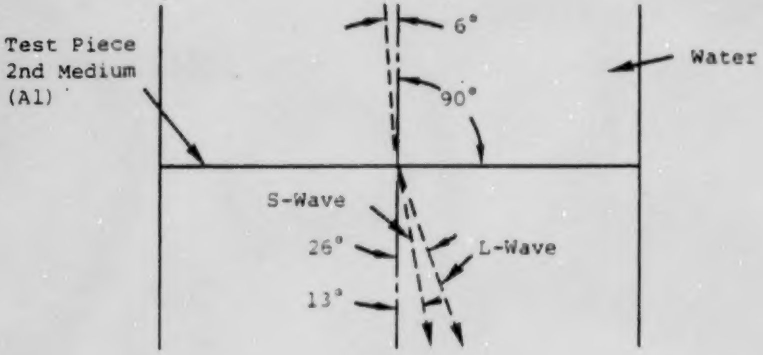


Figure 32-1-11. Illustration of Snell's Law

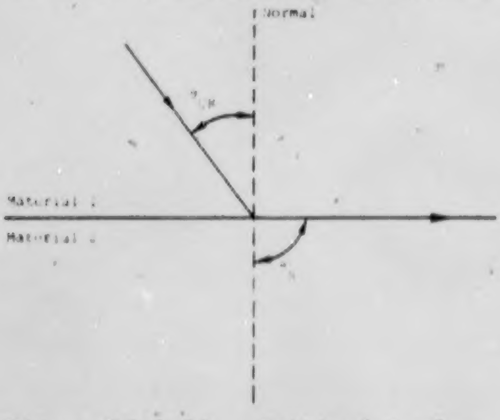


Figure 32-1-12. Critical Angle

EXAMPLE

Problem: What is the angle of refraction for: a) an L-wave, b) an S-wave?

Given: An ultrasonic wave in water is incident upon aluminum at 6° from the normal.

Solution:

$$\frac{\sin \theta_i}{\sin \theta_R} = \frac{C_1}{C_2} \text{ therefore, } \sin \theta_R = \frac{C_2}{C_1} \sin \theta_1$$

$\theta_1 = 6^\circ$ $\qquad$ $\sin \theta_1 = 0.105$

$C_1 = 1.48 \frac{\text{km}}{\text{sec}}$ $\qquad$ $C_{R\ell} = 6.30 \frac{\text{km}}{\text{sec}}$ $\qquad$ $C_{Rt} = 3.13 \frac{\text{km}}{\text{sec}}$

a) $\sin \theta_R = \frac{6.30}{1.48} \times 0.105 - 0.445$

$\theta_R = 26.4^\circ$ for L-wave

b) $\sin \theta_R = \frac{3.13}{1.48} \times 0.105 - 0.221$

$\theta_R = 1.27^\circ$ for S-wave

Critical Angles

Critical angle is the angle of incidence where sin θ refraction is unity. At the critical angle, a surface wave is propagated and above the critical angle, the ray is totally reflected.

Table 32-1-3. First Medium is H_2O[1]

Test Material	1st Critical Angle	2nd Critical Angle
Beryllium	7°	10°
Aluminum, 175T	14°	29°
Steel	15°	27°
Stainless, 302	15°	29°
Tungsten	17°	31°
Uranium	26°	51°

Table 32-1-4. First Medium is Plastic[1]

Test Material	1st Critical Angle	2nd Critical Angle
Beryllium	12°	18°
Aluminum, 175T	25°	59°
Steel	27°	56°
Stainless, 302	28°	59°
Tungsten	31°	68°

EXAMPLE: 32-1-5

Problem: What are the critical angles for L-waves and S-waves?

Given: Ultrasonic waves in water incident upon aluminum.

Solution:

For a critical angle, $\sin \Theta_R = 1$, therefore

$$\sin \Theta_i = 1 \times \frac{C_i}{C_R}$$

a) $\sin \Theta_{i_{CR}} = \frac{1.48}{6.30} = 0.235$

$$\Theta_{i_{CRIT}} = 13.6^\circ \text{ for L-waves}$$

This is called the first critical angle.

b) $\sin \Theta_{i_{CR}} = \frac{1.48}{3.13} = 0.0473$

$$\Theta_{i_{CRIT}} = 28.2^\circ \text{ for S-waves}$$

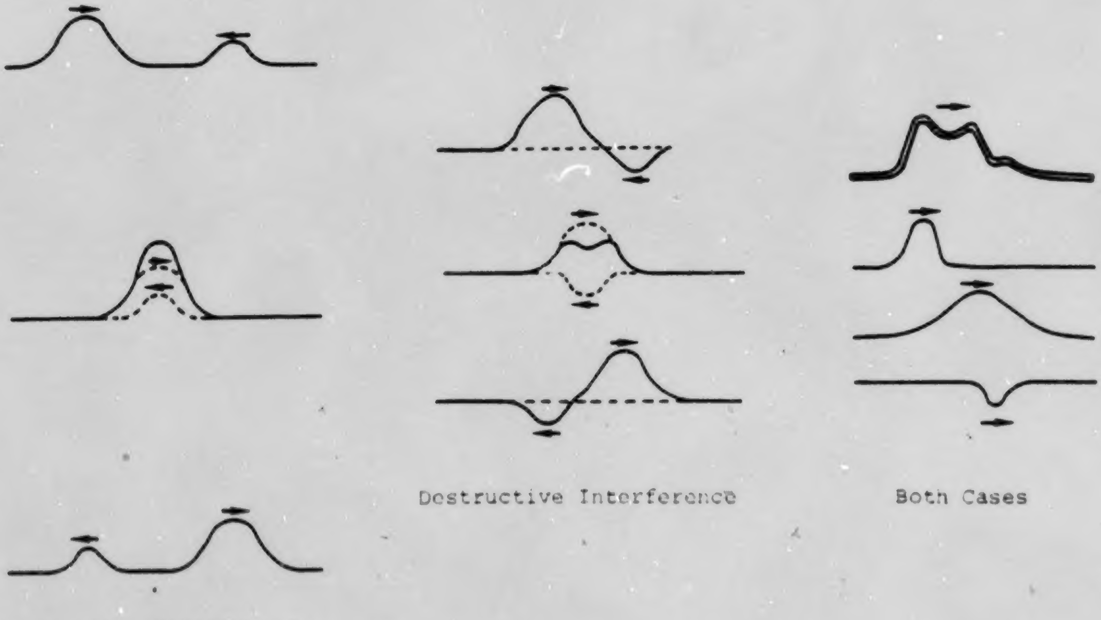
This is called the second critical angle.

---

[1] Ultrasonic Testing, General Dynamics Convair Division, San Diego, California, 1967.

Interference and Standing Waves

When two waves pass through each other, or superpose, their amplitudes add to each other at every point they overlap. This process is called interference. When two or more wave's amplitudes add in such a manner as to increase the resulting amplitude, the process is referred to as constructive interference. When two or more wave's amplitudes add in such a manner as to decrease the resulting amplitude, the process is referred to as destructive interference. Both, of course, may be present in one interaction. Figure 32-1-13 gives schematics of each case for pulses.



Constructive Interference

Destructive Interference

Both Cases

Figure 32-1-13. Superposition

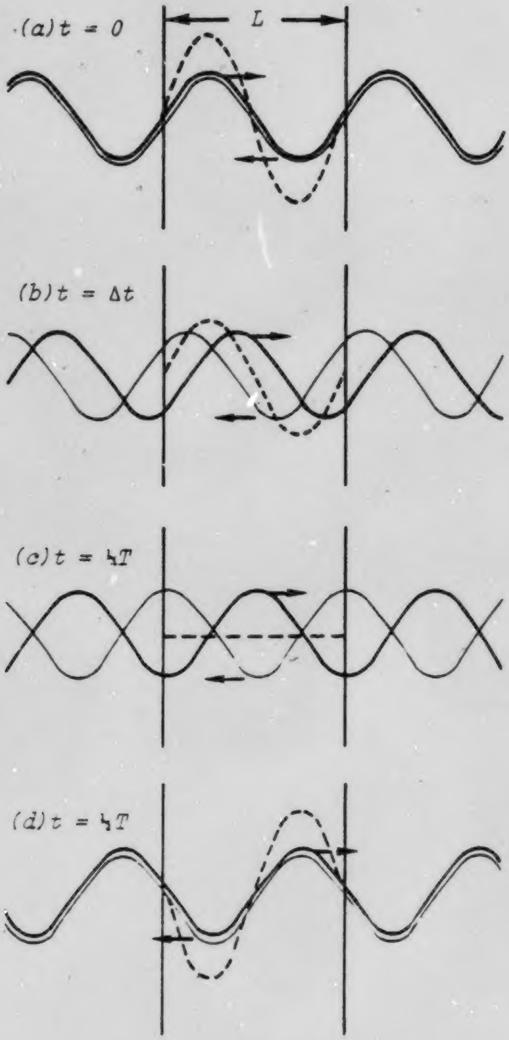

L
(a) t = 0
(b) t = Δt
(c) t = ¼T
(d) t = ½T

Figure 32-1-14. Standing Waves

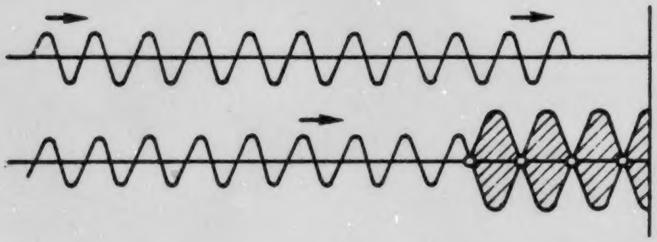


Figure 32-1-15. Standing Waves from a Free Wall

For long duration periodic waves of the same frequency, a very special phenomenon can occur for waves of the same frequency, amplitude, and direction of propagation: standing waves. In standing waves, the waves appear not to propagate but seem to oscillate in place. This is easiest to visualize in the special case of two waves propagating in exactly opposite directions.

When the two waves superpose, as in Figure 32-1-14, their amplitudes will add as previously discussed. However, at certain points called nodes, the addition will always be destructive. Between these points the waves will appear as single oscillations in place, with a maximum amplitude of twice either individual wave.

When a wave is reflected from a free boundary, one where the acoustic impedance is significantly less in the second material, the reflection occurs at an antinode. See Figure 32-1-15. A typical free boundary is the steel-air interface at the surface of a test sample (going from steel to air).

When a wave is reflected from a clamped boundary, one where the acoustic impedance is significantly greater in the second material, the reflection occurs at a node. See Figure 32-1-16.

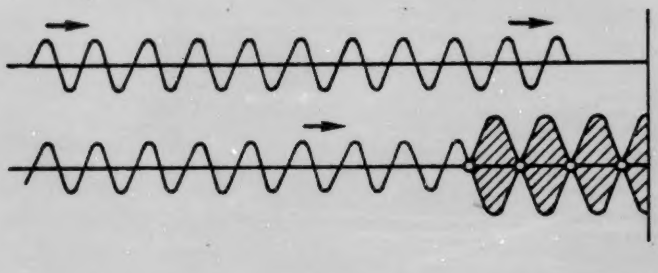


Figure 32-1-16. Standing Waves from a Fixed Wall

Standing waves are used in ultrasonic testing in resonance testing to measure wall thickness. Elsewhere, one should go to great lengths to avoid standing waves as they can be a major source of confusion and/or error.

Acoustic Impedence

The acoustic impedance determines what portion of acoustic energy incident upon an interface is reflected and what is transmitted. Sometimes, known as sound resistance, the acoustic impedance is defined as the product of a material's velocity of sound and its density.

$Z = \rho c$ Equation 32-1-6.

Z = Acoustic Impedance

ρ = Density

c = Velocity of Sound

The densities, velocities of sound, and acoustic impedances of some materials of interest are given in Table 32-1-5.

Table 32-1-5. Sonic Properties

Material	Density (gm/cm^3)	Velocity of Sound ($\frac{km}{sec}$)	Acoustic Impedance (gm/cm^2 -sec)
Steel	7.85	5.90	4.63
Aluminum	2.71	6.30	1.72
Water	1.00	1.48	0.148
Air	0.00129	0.33	0.00004

The fraction of the incident wave's energy reflected for an incident angle of 0° (normal) is given by the formula:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 \quad Z_1} \right)^2 \qquad \text{Equation 32-1-7}$$

The reflection coefficient (R) is the ratio of the reflected and incident beam intensities.

Where:

R = reflection coefficient

Z = Acoustic impedance

The fraction of incident energy transmitted for normal incidence is given by:

$$T = \frac{4Z_2Z_1}{(Z_2 + Z_1)^2} \qquad \text{Note: } R + T = 1 \qquad \text{Equation 32-1-8}$$

Where:

T = Transmission Coefficient

Z = Acoustic Impedance

The transmission coefficient (T) is the ratio of the transmitted and incident beam intensities.

EXAMPLE: 32-1-6

Problem: Find R and T

Given: A steel - aluminum interface.

Solution:

$Z_{Al} = 1.72 \qquad Z_{St} = 4.63$

$$R = \left(\frac{4.63 - 1.72}{4.63 + 1.72}\right)^2 = \left(\frac{2.91}{6.35}\right)^2 = \left(\frac{2.91}{6.35}\right)^2 = 0.46^2 = 0.21$$

$$T = \frac{4 \times 4.63 \times 1.72}{6.35^2} = \frac{31.82}{40.32} = 0.79$$

Beam Spreading

Compared to audible sound, ultrasound spreads very little while propagating through matter. Since the divergence of a wave beam is dependent upon wavelength, i.e., a short wavelength diverges very slowly, the shorter wavelengths or higher frequencies approach very closely to a straight-sided projection of the side of the transducer. In reality, however, there is always some spreading of the beam.

If the diameter of the transducer is given by D, the beam begins to spread at a distance $D^2/4\lambda$ from the transducer. Out to this distance the ultrasonic beam is said to be in the "near field", beyond, it is in the "far field". The far field appears to be a cone with its vertex at the center of the transducer face. See Figure 32-1-17 on the following page.

The rate of spread in the far field can be calculated from the formula:

$$\sin \frac{\theta}{2} = 1.22 \left(\frac{\lambda}{D}\right) \qquad \text{Equation 32-1-9}$$

Where:

θ = Vertex angle of the far field cone.

λ = Wavelength

D = Diameter of Probe Face

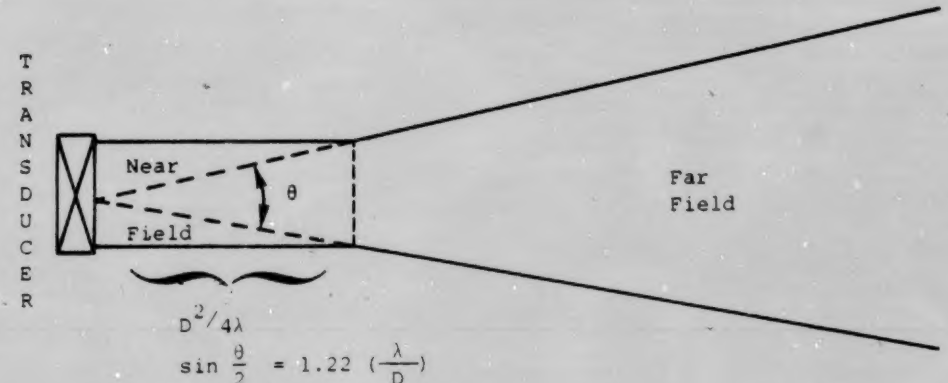

T
R
A
N
S
D
U
C
E
R
Near
Field
θ
Far
Field
$D^2/4\lambda$
$\sin\frac{\theta}{2} = 1.22\left(\frac{\lambda}{D}\right)$

Figure 32-1-17. Ultrasonic Beam Spreading

EXAMPLE: 32-1-7

Problem: What is the length of the near field?

Given: A:2 MHz UT procedure in steel with a 1 inch probe.

Solution: $L = \frac{D^2}{4\lambda} = \frac{(25.4\text{mm})^2}{4 \times 2.9\text{mm}}$

$L = 54.6 \text{ mm} = 5.46\text{cm} = 2.1 \text{ in.}$

EXAMPLE: 32-1-8

Problem: What is the half-angle spread for the far field?

Given: Same as Example 32-1-7.

Solution: $\frac{\Theta}{2} = \sin^{-1} (1.22 \frac{\lambda}{D}) = \sin^{-1} (1.22 \times 2.9/25.4)$

$\frac{\Theta}{2} = \sin^{-1} (0.14) = 8.0^{\circ}$

Table 32-1-6. Beam Spread in Steel = $\frac{\Theta}{2}$

$C\ell = 5900 \frac{m}{sec}$		Transducer Diameter (in.)			
Frequency (MHz)	λ(mm)	3/8	1/2	3/4	1
0.50	11.8	-*	-*	49.1°	34.5°
1.00	5.9	49.1°	34.5°	22.2°	16.5°
5.00	1.2	8.7°	6.5°	4.3°	3.2°
15.00	0.4	2.9°	2.2°	1.4°	1.1°

*D must be larger than λ to use this formula, and 1/2 in. = 12.7mm, therefore, 3/4 in. is the minimum diameter for the formula.

Table 32-1-6 shows the dependence of beam spreading upon frequency and transducer diameter. By increasing either, you may reduce beam spread, but it should be noted that there other considerations than spreading which may be affected by changing frequency or beam diameter, such as attenuation and necessity to precisely locate a small flaw.

Attenuation

Attenuation of ultrasonic waves is due to two main mechanisms: scattering and absorption. These two phenomena can be combined into the single concept of attenuation or extinction.

Scattering results from inhomogeneities in the material. The inhomogeneities may be either large or small scale. The large scale class includes pores and inclusions (impurities) and mixed crystalline structures (as in brass and steel). The small scale class essentially refers to the scattering of the waves off of the boundaries of the microscopic crystalline structure when the crystals are oriented randomly.

Absorption is the direct conversion of sound energy into heat. Several processes are involved, but since each is quite complicated they fall beyond the purpose of this module and will not be further treated. An approximate picture of absorption can be imagined if the wave oscillations are treated as being friction - braked, which causes them to die out and converts their energy to heat.

Both processes affect the ultrasonic testing process. Pure absorption merely weakens all signals and is easily remedied. You only have to increase the amplitude output of the receiver-amplifier. Scattering introduces spurious echoes or noises, which must either be ignored or electronically suppressed. Both types of attenuation increase with frequency, making the attenuation losses for a 12 MHz signal much greater than for a 1 MHz signal.

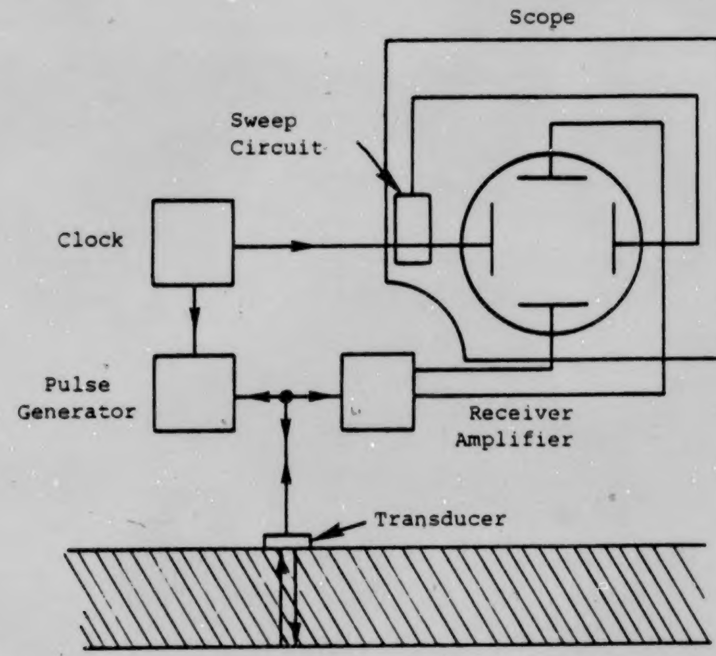
ULTRASONIC TEST EQUIPMENT

Basic Equipment

Each manufacturer of ultrasonic test equipment builds in features that are peculiar to that particular brand, but all general purpose units are, in broad terms, fairly similar. The usual way to break a unit into components is by function: the power supply, pulse generator, receiver-amplifier, clock, oscilloscope, and transducer assembly or probe. This description is for an A-scan pulse echo instrument which is, by an extremely large margin, the most common ultrasonic test equipment in use.

The power supply provides the energy to each of the other components of the instrument. It usually draws on 120V or 240V AC line power, although many portable instruments are battery driven.

The pulse generator or pulser, produces an electronic pulse at the desired frequency when triggered by the clock. The primary frequency, the pulse duration, the profile of the pulse envelope, and the pulse repetition rate may or may not be variable. This pulse is then transmitted to the probe.


Scope
Sweep Circuit
Clock
Pulse Generator
Receiver Amplifier
Transducer

Power supply not shown.

Figure 32-1-18 A-Scan Test Setup

The receiver-amplifier takes the return signal from the probe and amplifies it and otherwise processes it for display or data processing. The output signal from the receiver is customarily fed into an oscilloscope.

The oscilloscope displays the signal from the receiver amplifier in one of two modes: RF (radio-frequency) mode or video mode. The oscilloscope gives complete waveforms in the RF mode, but only peak intensities are shown in video mode. Some units operate on only RF or video while others allow for selection of either by the operator.

The clock is an electronic device which produces logic pulses and reference voltages and waveforms. These pulses, voltages, and waveforms serve to coordinate the operation of the instrument.

The probe has a transducer as its main component. A transducer either mechanically vibrates in response to an applied voltage, or produces a voltage in response to an applied mechanical vibration. The former is a sending transducer and the latter a receiving transducer. Transducers will be more completely discussed in a later section. Included in the probe unit will be cables, a housing, and a damping material affixed to the transducer.

Typical Controls

While different manufacturers of ultrasonic test equipment all have at least slightly different control setups, there are at the same time enough similiarities in basic functions that wildly divergent versions are not too common. Therefore, an introduction to the basic panel of a simple unit, as pictured in Figure 32-1-19 is in order.

The power supply is virtually always controlled by switch(es), frequently built into a rheostat controlling some other function, such as grid illumination. The power supply may also have a built-in time delay to protect the rest of the instrument during warm-up and will itself be protected by fuses.

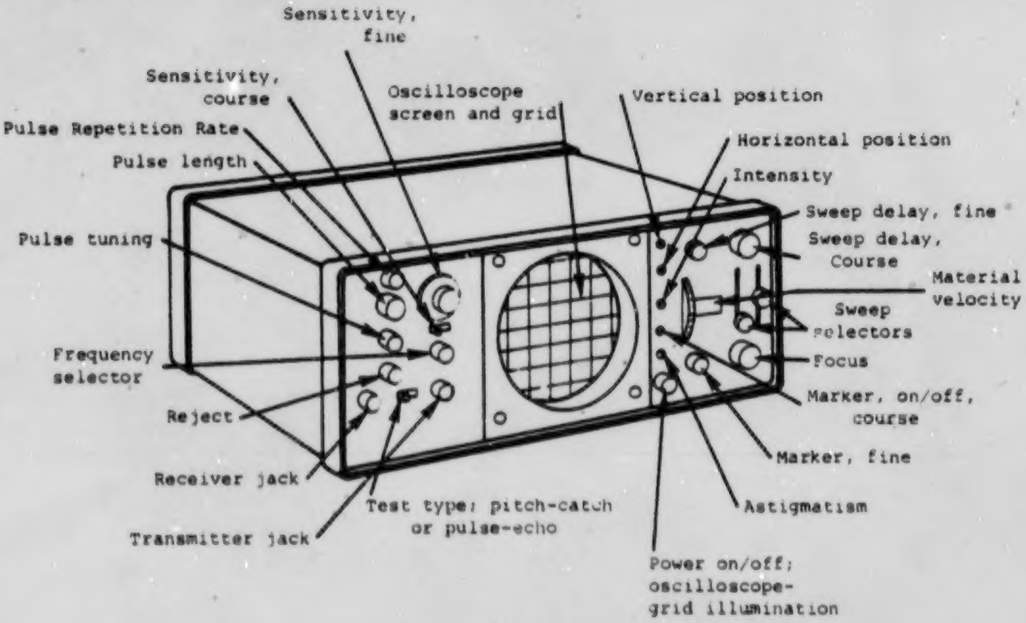

Sensitivity, fine
Sensitivity, course
Oscilloscope screen and grid
Vertical position
Pulse Repetition Rate
Horizontal position
Pulse length
Intensity
Sweep delay, fine
Pulse tuning
Sweep delay, Course
Material velocity
Sweep selectors
Frequency selector
Focus
Reject
Marker, on/off, course
Marker, fine
Receiver jack
Test type; pitch-catch or pulse-echo
Astigmatism
Transmitter jack
Power on/off; oscilloscope-grid illumination

Figure 32-1-19. Typical pulse-echo instrument

The controls for pulse manipulation adjust the pulse repetition rate, the pulse length and pulse tuning or envelope shaping. The principle pulse frequency range is selected by a knob marked frequency.

The transducer cable(s) is(are) connected to the unit through the T (or transmitter) jack for single transducer procedures and through the T and R (or receiver) jacks for two transducer procedures. Which configuration is active is controlled by a selector switch which is usually labeled test-type.

The receiver-amplifier's gain is controlled by a single switch or a pair of switches marked sensitivity. The two switch set-up is usually a division by degree, into coarse and fine sensitivity.

With the exception of timing functions and grid illumination, most of the oscilloscope controls are usually of the set screw type as they require only infrequent adjustment. The set screw controls are:

- Vertical position
- Horizontal position
- Brightness
- Focus
- Astigmatism

The timing controls adjust sweep rate and delay time controls. The sweep delay time is used to position the initial pulse on the screen. The sweep delay can be used to eliminate water transmission times in immersion testing.

The sweep rate adjusts the length of the horizontal sweep or baseline moving signals to the right of your starting point. The grid illumination control frequently includes the main power switch.

There are several controls which may be present on the more sophisticated apparatus, such as mode selection, switch, marker circuit controls, driving voltage selector and gated alarm units. The mode selection switch allows the selection of either RF or video modes. If a marker circuit is included, there will be an on/off switch and a frequency selection. The driving voltage selector matches the output of the pulse generator to special transducers. The gates alarm units, which trigger visible, audible, or electronic alarms upon detection of a flaw in a specific region of the test material, generally have three controls. They are leading edge or beginning of gate position, width of gate or trailing edge of end of gate position, and a threshold or sensitivity control which sets the minimum return signal height to trigger the alarm.

Transducers

Virtually all ultrasound transducers are piezoelectric devices, with the exception of a few low frequency devices used to test materials such as concrete and rock which will not be covered in this module. Piezoelectric materials have two basic properties that are of interest to the ultrasonic test technician. The first is the direct piezoelectric effect and the second the inverse piezoelectric effect. The direct effect is used in detecting mechanical vibrations, the inverse effect in producing mechanical vibrations. The name piezoelectricity is from the Greek for "pressure electricity".

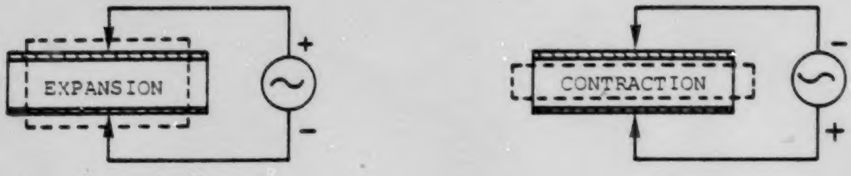


Figure 32-1-20 Piezoelectric Effect

As the name implies, a piezoelectric material develops an electric charge on its surface when deformed by an external mechanical force. This physical principle was discovered in 1880. By 1881, the inverse piezoelectric effect was discovered wherein the application of an external electric field causes a piezoelectric material to deform.

The most important transducer materials are quartz (SiO_2) first, followed by lithium sulfate ($LiSO_4$), barium titanate ($BaTiO_3$), and lead metaniobate ($PbNb_2O_6$). The first two are natural piezoelectric crystals, the second pair consists of polarized, or artificially made piezoelectric materials. There are other materials intended for special applications, but the four listed above are far and away the most commonly used.

The oldest piezoelectric material, quartz is chemically resistant and very hard, being slightly harder than tempered steel. All the other piezoelectric materials are much less chemically resistant. Quartz also has the advantage of only needing a back surface contact, the face of the metal being tested can be the front surface contact.

Barium titanate is the best transmitter material, and lithium sulfate is the best receiver material if viewed only in terms of the size of mechanical oscillations possible to the crystals, but lead metaniobate matches the sound transmission of most test materials well and can produce very short pulses making it the best all around material, excepting a lack of durability when compared to quartz, for ultrasonic testing.

Physically, a transducer consists of an active element or crystal, a damping body, and the housing. The crystal is the piezoelectric material and has a metallic coating on its front and back surfaces to act as electrodes.

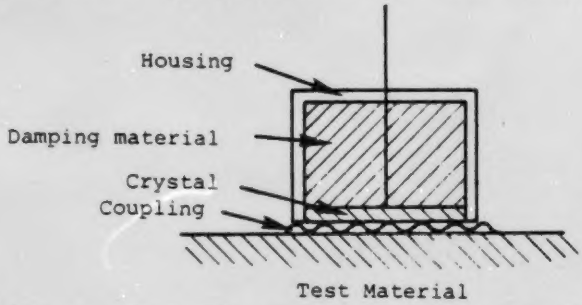


Figure 32-1-21 Transducer or Probe

The thickness of the crystal is not extremely critical, but for most efficient operation, a crystal should oscillate at its fundamental frequency. The fundamental frequency at which any substance can vibrate is the frequency corresponding to a wavelength equal to twice its thickness.

$$d = \frac{\lambda}{2} = \frac{1}{2}\frac{c}{f} \qquad \text{Eq 32-1-10}$$

Where

d = thickness

λ = wavelength

c = velocity

f = frequency

EXAMPLE: 32-1-9

Problem: What thickness(es) must a quartz plate have to oscillate at the following frequencies?

Given: (a) 2 kHz (b) 2 MHz

$C = 5.76 \frac{\text{km}}{\text{sec}}$

Solution:

(a) $d = \frac{\lambda}{2} = \frac{1}{2}\,\frac{c}{f} = \frac{1}{2}\,\frac{5.76\ \text{km/sec}}{0.002\ \text{MH}_2} = 1.44(10)^3\text{mm}$

$= 1.44\text{m}$

(b) $d = \frac{1}{2}\,\frac{c}{f} = \frac{1}{2} \times \frac{5.76}{2} = 1.44\text{mm}$

A piezoelectric crystal can be excited to its fundamental frequency by applying to its surface electrode an AC potential at that frequency.

The damping block may serve several functions. Most importantly, of course, the damping block "damps out" or rapidly attenuates the oscillations of the crystal in order to permit very short oscillations of the crystal. The damping block should also absorb the back surface waves along with any other waves entering it to avoid interference, especially with single probe operation. Also, it can supply mechanical support to thin crystals.

Not all transducers have integral damping. For pulses that are not especially short and a surface that is very smooth, the damping due to the coupling may be quite satisfactory. When tests are to be repeated frequently, a crystal may be cemented directly to the test specimen, which will damp the crystal quite well.

The oscillator crystal and the damping block are normally fitted into a housing or casing which mechanically secures them in position. In addition, the housing electrically screens the crystal and for the unprotected quartz probes the casing provides the lead to the front surface electrode, i.e., the metal surface of the test material.

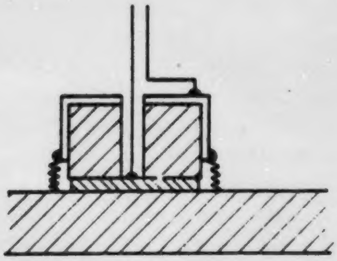


Figure 32-1-22 Electrical Connections to a Probe

The connecting cables are generally co-axial to shield the signals from ambient noise signals.

To get the signal from the transducer into the test material even very thin layers of air between them must be avoided. Since surfaces of materials are never perfectly flat a material, usually liquid, that is a better conductor of sound than air is used to "couple" the transducer and the test piece.

Couplants in common use include water, water plus glycerin, glycerin oils, petroleum and silicon greases, wallpaper paste, and very soft types of rubber. Separate couplants are, or course, not necessary for immersion testing.

Water, while a fair coupling agent, may have to be made wetter by the addition of a wetting agent such as glycerin to reduce its surface tension. Since glycerin has excellent acoustic properties, this may further improve the coupling.

The most frequently used couplant for contact tests is medium viscosity oil, grade SAE 20 or 30. This is especially true in testing steel in order to avoid corrosion as might be experienced with water. When testing non-horizontal or inverted surfaces, petroleum-based or silicon-based grease is recommended to avoid dripping. However, they are quite messy and expensive and wallpaper paste may be utilized instead, with soluble phosphates added to reduce corrosion.

Special Oscilloscope Notes

Since the oscilloscope is the basic means of presenting test data to the technician, he or she should understand how it operates. Oscilloscopes are divided into two classes or types depending on how they deflect the electron beams. The electromagnetic type uses magnetic fields to deflect the electrons and the electrostatic type uses electric fields. Only a few test oscilloscopes use electromagnetic deflection, most are electrostatic.

The heart of the oscilloscope is the cathode ray tube (CRT) which produces and directs electrons, causing them to trace out patterns on the fluorescent coating on the inside of its front surface causing it to glow.

The electrons are emitted from a heated cathode and accelerated by the anode(s) to speeds over 10^7 m/sec. These assemblies are frequently grouped together as the electron gun.

The deflection plates cause the stream of electrons to move both horizontally and vertically, there being a pair of plates oriented in each direction. The force of deflection is produced by the interaction of the electrons and the electric fields between the plates.

The vertical deflection is driven by the output of the receiver-amplifier with positive voltages being displayed upwards and negative downwards. The horizontal display is driven by the output of the sweep circuit, which in most ultrasonic test equipment is triggered by the clock. The waveform produced by the sweep is a "sawtooth" pattern sweeping the beam evenly across the screen, from left to right, and then providing a relatively rapid "flyback" or retract to restart the pattern, as seen in Figure 32-1-23.

This basic pattern is repeated frequently enough to provide a "continuous" trace just as motion pictures are successive photographs shown frequently enough to provide a continuous picture. In ultrasonic testing there will therefore be a horizontal line when no signal is being received by the receiver-amplifier. This horizontal line is known as the baseline. The length of the baseline is proportional to the length of time necessary to sweep from left to right.

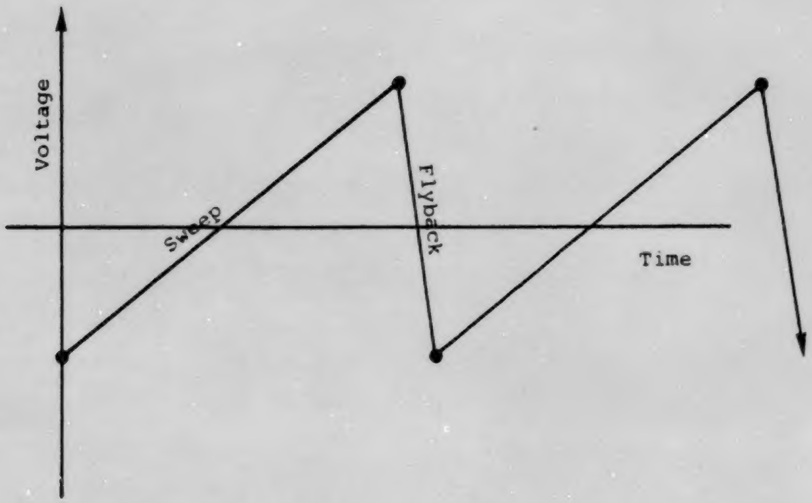


Figure 32-1-23 Sawtooth Voltage Waveform

Therefore, the distance along the baseline represents time which is proportional to distance travelled at a constant velocity. This enables an operator to adjust the horizontal sweep to a distance scale, so that distances in a material may be directly read on the face of the CRT.

If signal pulses are being received by the CRT, the vertical circuit will deflect the electron beam in such a way as to cause corresponding pulses or pips to appear on the screen. When reflection signals from the front surface, a discontinuity, and the back surface are displayed on the screen, the separation between them can be determined from their spacing on the screen. The section on testing will cover this in more detail.

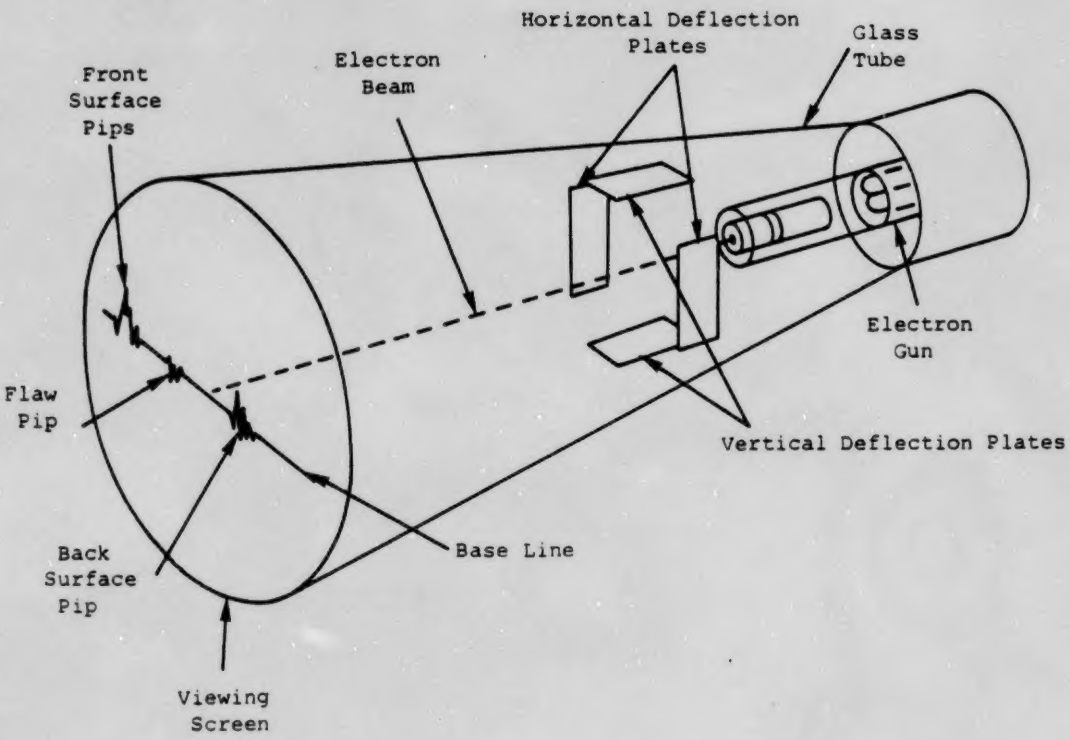

Horizontal Deflection Plates
Glass Tube
Electron Beam
Front Surface Pips
Electron Gun
Flaw Pip
Vertical Deflection Plates
Back Surface Pip
Base Line
Viewing Screen

Figure 32-1-24 Typical Cathode-Ray Tube

TEST PROCEDURES

There are four (4) basic categories of procedures for ultrasonic testing if the procedures are being characterized by the variable being measured. Those categories are: resonant frequency method, intensity methods, transit time method, and intensity and transit time methods.

The resonance frequency method employs standing waves to measure sample thickness while the transit time method uses time of flight to measure thickness. The various intensity methods can be used to detect flaws but since no time measurements are made, no information about flaw depth can be obtained. The most comprehensive methods, and the most widely used, are the intensity and transit time methods. These can be used to locate flaws with precision.

Resonance Frequency

The resonance frequency method is the oldest non-destructive testing technique when you consider audible sound. Ceramics and metals were tested by listening to how the material "rang" when struck. There are sophisticated versions of this still in use, using complex electronics for excitation and analysis, but it has the drawback of only being able to detect large flaws at a size within approximately one order of magnitude of a wavelength of audible sound, which is several centimeters.

Ultrasonic resonance testing, however, can deal with quite small objects as the wavelength of ultrasound is much smaller than that of audible sound. The basic principle is the same as discussed in the previous section for crystal oscillations. Standing waves are set-up in a plate and their frequency used to calculate thickness by the formula.

$$d = \frac{1}{2} \frac{c}{f} \qquad \text{Eq 32-1-11}$$

Where

d = thickness
c = velocity
f = frequency

The problem with this approach is that it is very difficult to tell if a given standing wave pattern represents only a single half wavelength across the sample. The frequency associated with this wavelength is called the fundamental frequency.

Since other wavelengths are possible to standing wave patterns across a plate, it is therefore possible to have other frequencies. However, standing waves can exist only for thickness equal to an integral number of half wavelengths i.e.:

$$d = n\left(\frac{\lambda_n}{2}\right) \qquad \text{Eq 32-1-12}$$

Where

d = thickness
λ_n = wavelength
n = number of half wavelengths of wavelength λn.

Therefore, the thickness can be said to be equal to:

$$d = \frac{n}{2}\left(\frac{c}{f}\right) \qquad \text{Eq 32-1-13}$$

Where

d = thickness
n = number of half wavelengths
c = wave velocity
f = frequency

but you can't easily determine n.

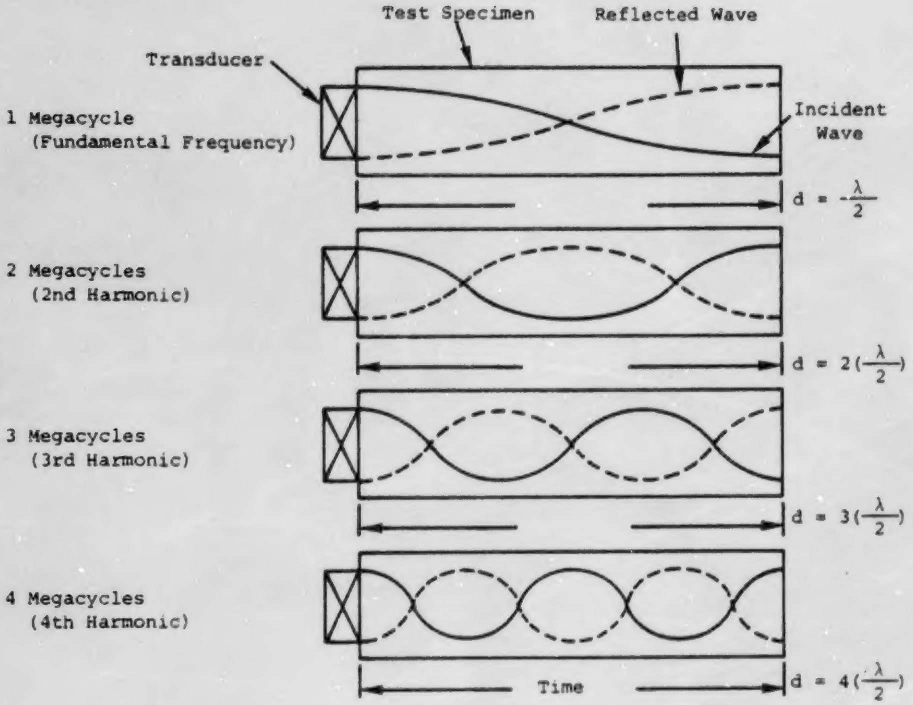

Test Specimen
Reflected Wave
Transducer
Incident Wave
1 Megacycle (Fundamental Frequency)
$d = \frac{\lambda}{2}$
2 Megacycles (2nd Harmonic)
$d = 2(\frac{\lambda}{2})$
3 Megacycles (3rd Harmonic)
$d = 3(\frac{\lambda}{2})$
4 Megacycles (4th Harmonic)
Time
$d = 4(\frac{\lambda}{2})$

Figure 32-1-25. Standing Wave Patterns for Various Harmonics

There is one fairly easy approach to simplifying this, however. You can operate over a wide range of frequencies and measure when the transducer is resonating with the plate. The reason for this can be shown as follows:

$$\text{for any value of } \lambda_n,\ C = \lambda_n f_n \qquad \text{Eq 32-1-14}$$

Where

c = velocity
λ = wavelength
f = frequency

$$\text{and } f_n = \frac{C}{\lambda_n} = \frac{nc}{2d} \qquad \text{Eq 32-1-15}$$

Where

f = frequency
c = velocity
λ = wavelength
n = number of half wavelengths
d = thickness

but therefore $f_1 = \frac{1c}{2d}$ Eq 32-1-16

which implies that $f_n = nf_1$ Eq 32-1-17

These frequencies called harmonics, overtones, or characteristic frequencies are equal to integral numbers of times the fundamental frequency and are therefore separated by just the fundamental frequency.

$$\Delta f = n\ f_1 - (n-1)\ f_1 = f_1 \quad \text{Eq 32-1-18}$$

Where

Δf = difference in frequencies
f = frequency
n = number of half wavelengths

To find the fundamental frequency, in other words, one merely has to find any two adjacent harmonics of the plate by changing the frequency of plate oscillation by changing probe frequency. This is detectable because the transfer of energy between the probe and the plate is most efficient at the plate's characteristic frequencies, or when the probe's crystal is in resonance with the sample. The condition of resonance is, in this case, easily detectable as the power, or current drawn by the crystal will increase dramatically, or spike, as the driving frequency sweeps through the resonance frequency.

A serious problem with this method is the uniformity of the crystal's response to the driving voltage. If the crystal is excited at one of its own characteristic frequencies, it will resonate with the driving circuitry and mimic a resonance with the plate. To avoid this, probes used in the resonance frequency test are always selected such that they will be excited below their fundamental frequency.

A second problem, that can not be so easily avoided, is the problem of coupling the probe to the test sample. The more efficient is the coupling between the probe and the test sample, as required for good sound transmission, the less independent is the response of the sample. The test sample and the probe become closely enough linked mechanically that they must be treated as one item responding to the oscillation, thus introducing an error by raising the resonant frequency. A way to reduce the relative error is to operate at as high a characteristic frequency as possible.

Once the fundamental frequency is known, thickness is easily found from Equation 32-1-19:

$$d = \frac{c}{2f_1} \qquad \text{Eq 32-1-19}$$

Where

d = thickness
c = velocity
f_1 = fundamental frequency

EXAMPLE: 32-1-10

Problem: Find the thickness of a sheet of aluminum using data from a resonance frequency test for process control.

Given: Harmonic peaks are detected at 2.03 MHz, 2.65 MHz, 3.26 MHz, and 3.84 MHz.

Solution: $f_1 = f_{n+1} - f_n = \Delta f_n$

$$\Delta f_1 = 3.84 \text{ MHz} - 3.26 \text{ MHz} = 0.58 \text{ MHz}$$

$$\Delta f_2 = 3.26 \text{ MHz} - 2.65 \text{ MHz} = 0.61 \text{ MHz}$$

$$\Delta f_3 = 2.65 \text{ MHz} - 2.03 \text{ MHz} = 0.62 \text{ MHz}$$

$$f_1 = \overline{\Delta f} = 0.603 \text{ MHz}$$

$$d = \frac{c}{2f_1} = \frac{6.30 \frac{\text{km}}{\text{sec}}}{2 \times 0.603 \text{ MHz}} = 5.22\text{mm} = 0.206 \text{ in.}$$

In practice, most test instruments in use today will directly display the thickness on an oscilloscope screen, generally by some form of overlay to the screen. A typical overlay is shown in Figure 32-1-26. The CRT screen itself displays frequency horizontally and peaks will therefore indicate the harmonic frequencies. To avoid confusion as to which harmonic is being displayed, at least two peaks are usually shown, as in Figure 32-1-26.

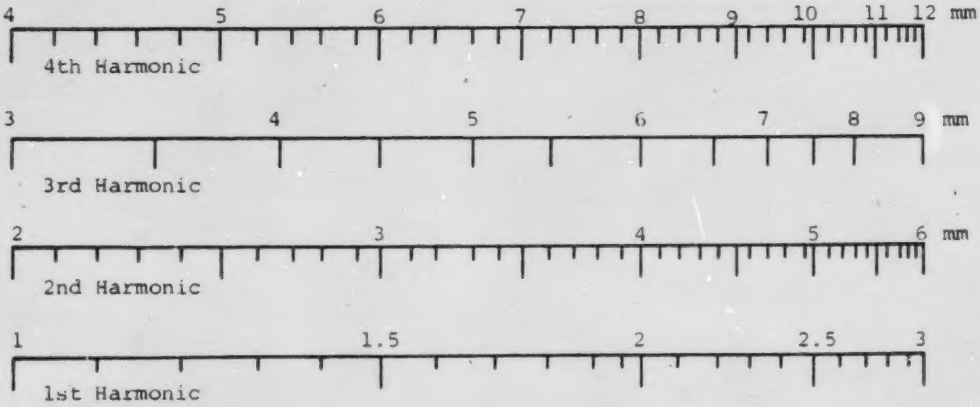

4
5
6
7
8
9
10
11
12 mm
4th Harmonic
3
4
5
6
7
8
9 mm
3rd Harmonic
2
3
4
5
6 mm
2nd Harmonic
1
1.5
2
2.5
3
1st Harmonic

Figure 32-1-26 Overlay for oscilloscope for resonance frequency test.

When the overlay scale is correctly matched to the probe in use, generally by being color-coded or otherwise identically marked, each peak is read off its own scale. While each harmonic is by itself indistinguishable from others, the thickness can be read from the scales that match each other as in Figure 32-1-27.

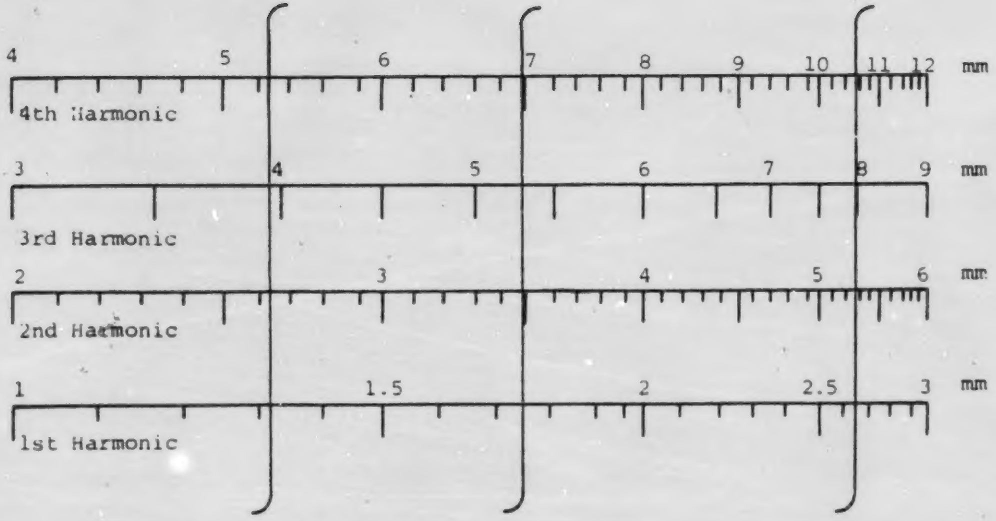

4
5
6
7
8
9
10
11
12
mm
4th Harmonic
3
4
5
6
7
8
9
mm
3rd Harmonic
2
3
4
5
6
mm
2nd Harmonic
1
1.5
2
2.5
3
mm
1st Harmonic

Figure 32-1-27 Oscilloscope display with overlay for resonance frequency test. The harmonics are the second and third and match at approximately 4:30 min.

EXAMPLE: 32-1-11

Problem: In a resonant frequency test for wall thickness of a pipe, how can the results be shown to be 4.30 mm?

Given: The display of Figure 32-1-27.

Solution: The first resonance peak intercepts the scales at 1.43 mm, 285 mm, 4.3 mm, and 5.7 mm.

The second peak intercepts the scales at 2.16 mm, 4.30 mm, 6.45 mm, and 8.3 mm.

The only match is at 4.3 mm, therefore, that is the thickness as measured.

When wall thickness measurements are made on smooth surfaces, sharp spikes or peaks are produced, but rough surfaces reduce the height of the resonances and smear them out over relatively wide bands of frequencies. This has two implications for actual testing. Firstly, it can be used as a testing method for checking the condition of inaccessible surfaces. Secondly, it means that great care must be taken to smooth the front surface by grinding and sanding.

One note about resonance frequency testing: if the sample has non-parallel sides, or an included flaw is inclined to the surfaces, the amplitudes of the resonant peaks may be reduced by any amount from a slight reduction to extinction.

Resonance testing uses many individual types of test instruments, both visual and audible data displays; many manufacturers and models; and even many different components for each model. As a result, all that can be reasonably said is that it is best to consult the manuals provided with each machine for operating details.

Intensity Method

The intensity method is actually a group of four techniques which measure the amplitude of ultrasound after propagation through a test piece. The four (4) techniques are the transmission method, reflection method, conduction method, and image projection method.

The first three(3) differ only in the positioning of the probes and/or the relative sizes of the test sample and the wavelength being used.

Transmission Method

The transmission method uses a high frequency generator to drive a transmitting probe which in turn continuously generates, ideally, plane waves propagating perpendicularly to the surface. After a single pass through the material, a receiving probe picks up the signal and passes it through to a receiver-amplifier which outputs to a gauge or some other instrument as shown in Figure 32-1-28. This is referred to as a continuous beam method. The receiving probe should be directly opposite to and aligned with the sending probe.

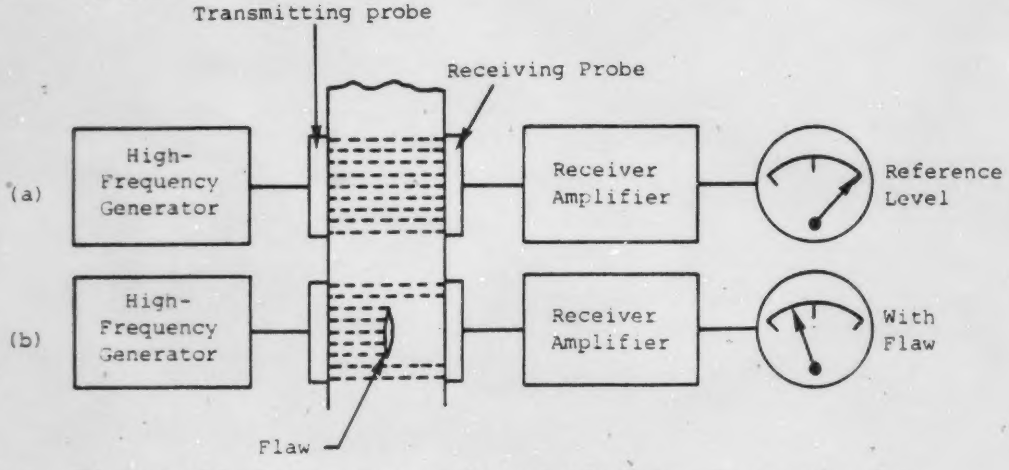

Transmitting probe
Receiving Probe
(a)
High-Frequency Generator
Receiver Amplifier
Reference Level
(b)
High-Frequency Generator
Receiver Amplifier
With Flaw
Flaw

Figure 32-1-28 Intensity Method by Transmission

The signal through an unflawed region or test sample is used as a reference level. When a flaw blocks a portion of the beam, a signal reduction will be measured at the output gauge, indicating the presence of a discontinuity. The drawback to this method is that there is no way to determine the depth or orientation of the flaw.

Reflection Method

The reflection method uses an interface of the material to reflect a beam, usually back to the surface from which it was transmitted. In most other ways, it is identical to the transmission method. The most important difference is that the probes are angled to allow for separation of the receiver and transmitter. The probes are angled because this is a continuous wave method, and only pulsed methods can use the same transducer for transmission and reception.

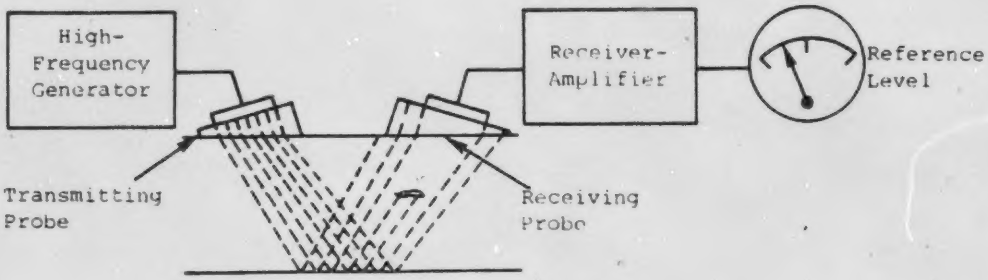


Figure 32-1-29 Intensity Method by Reflection

A major advantage of the reflection method, compared to the transmission method, is that only one accessible surface is needed.

Conduction Method

The third intensity method is the conduction method. The conduction method generally applies to small test samples, where the wavelength of the test signal is very large compared to at least one dimension of the test sample. Because of the relative sizes of the test sample and test signal, there is no simple or "optical" path for the signal. There are reflections involved, of course, so this is closely related to the reflection method. And as in the reflection and transmission cases, the level of conduction in each case must be checked against some basis or reference level, which will be a similar test on an unflawed sample.

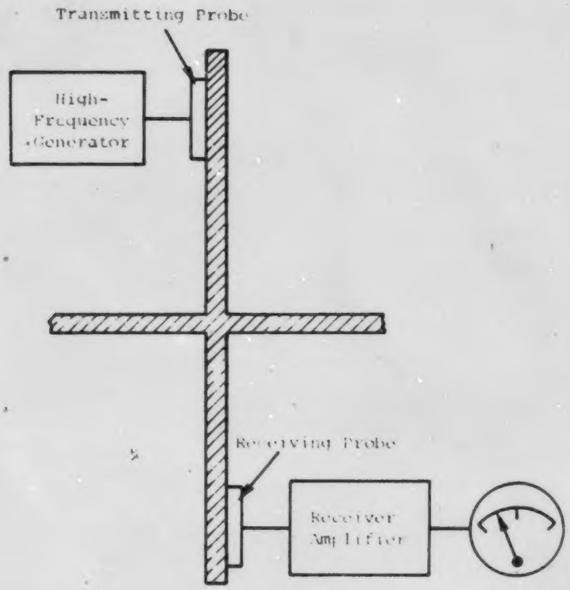


Figure 32-1-30 Intensity Method by Conduction

When dealing with continuous wave methods, as the intensity methods are, the test samples tend to become "filled up" with a three dimensional field of standing waves. Because no two test samples can ever be exactly alike, there will be widely varying patterns of nodes and anti-nodes in very similar appearing samples. Even a slight change of position (as small as one-half a wavelength) on an individual test sample can change received signal strength measurably.

In general wave propagation theory, there are two basic ways to break up this standing wave pattern. One is to change the entrance geometry of the waves as in the mode-mixing used in microwave ovens. The other is to quite rapidly vary or modulate the test frequency about some central value, thereby changing the wavelength and avoiding fixed patterns of standing waves.

The standing wave pattern can be smoothed out or "averaged" only if there is a path change of one-half wavelength over the modulation envelope. The required fractional change of frequency which is a function of frequency and plate thickness, can be very small for thick plates and therefore easily obtained, but can be very large for thin test samples. A large dynamic range is difficult to obtain in many transducers, which serves as a limit to the usefulness of this method.

The most important application of the intensity method is in the testing for laminar flaws in sheet metal by the transmission method. Also, it is best suited for automatically testing large numbers of identical (or nearly identical) test samples.

Intensity and Transit Time Methods

There are two types of intensity and transit time methods. The first type is the pulse transit time method, and the second is the frequency modulation method. The pulse transit time method may be split, as the intensity method was into transmission reflection, and conduction categories. The transmission and reflection methods along with the intensity method by transmission are the most important methods in ultrasonic testing. Pulse transit time by reflection is the single most widely used method and is known as the pulse-echo method.

Pulse-Echo Method

The pulse-echo method, as its name implies, uses short pulses of ultrasound and therefore avoids the problem of exciting a standing wave field in a test piece. Another advantage of the pulses operation is that a single probe can both send and then receive between sending pulses.

The pulse-echo method works in the same manner as active sonar. It sends out a pulse of ultrasound which is reflected back to the receiver by either a discontinuity or the back wall. The size of the peak of a return echo is proportional to the echo's amplitude and contains information about the size of the reflecting surface or flaw. The other information contained in the echo is the depth of reflecting surface or flaw, and this can be determined from the equation:

$$d = c \cdot t \qquad \text{Eq 32-1-20}$$

Where

d = distance

c = velocity

t = time

The depth, of course, is equal to one-half the round-trip distance travelled by the pulse, so:

$$d = \frac{c \cdot t}{2} \text{ for depth} \qquad \text{Eq 32-1-21}$$

EXAMPLE: 32-1-13

Problem: Echoes for the flaw and the backwall are received during a pulse-echo test of steel plate. What is the approximate:

(a) flaw depth?
(b) wall thickness?

Given: $t_{flaw} = 2$ Msec, $t_{bw} = 3$Msec, $c = 7000 \frac{m}{sec}$?

Solution: (a) $d = \frac{1}{2} \; ct = \frac{1}{2} \times 7 \; \frac{km}{sec} \times 2 \; \mu \; sec = \underline{\underline{7mm}}$

(b) $d = \frac{1}{2} \; ct = \frac{1}{2} \times 7 \; \frac{km}{sec} \times 3 \; \mu \; sec = \underline{\underline{10.5mm}}$

A-Scan

The basic pulse echo scheme of data display is the so-called A-scan, using the oscilloscope to present pulse height versus time of flight. Figure 32-1-31 shows a schematic view of an A-scan.

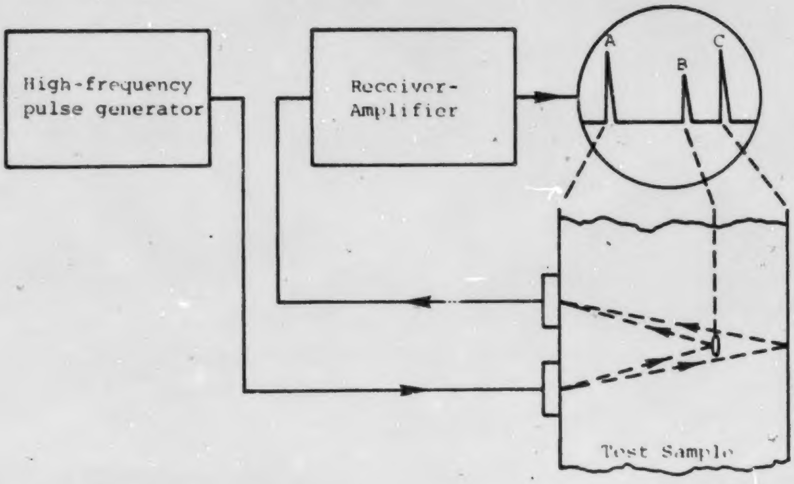


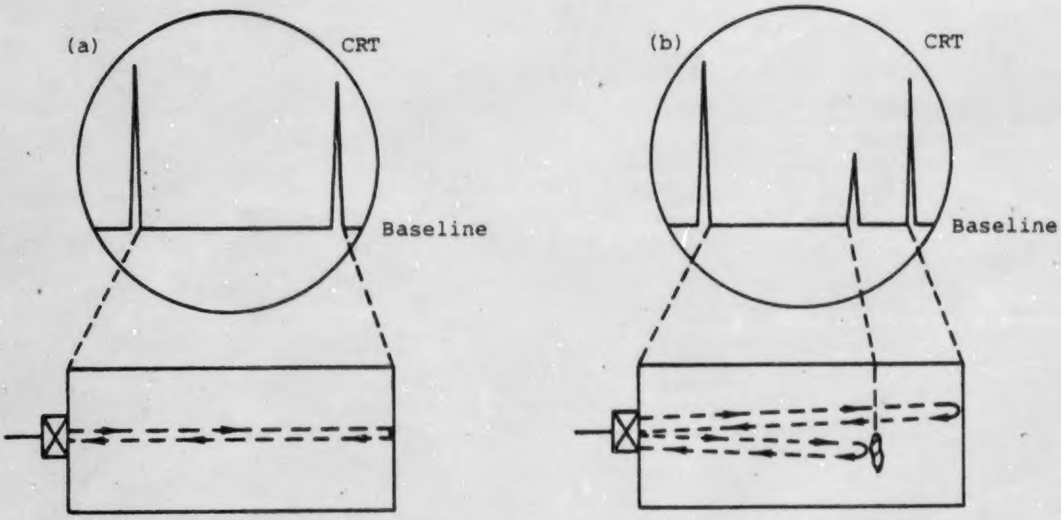
Figure 32-1-31 Pulse-echo Method, A-Scan.

The peak marked A in Figure 32-1-31, is the reflection off of the front surface of the test piece and is used as the reference for all time or depth measurements. The peak marked B is the reflection off of the flaw, and its amplitude is relatively small or inclined to the beam. In this case it is small. The peak marked C is the backwall echo and its position on the CRT corresponds to the thickness of the test object.

If the thickness of the test object is known beforehand, an A-scan device may be calibrated by setting the front surface and backwall peaks on grid lines on the CRT face and simply reading depths of intermediate echoes, flaws for instance, from the grid lines. If, however, thickness is not known, the device may be calibrated using test blocks or the internal marked circuitry, and then the thickness can be measured.

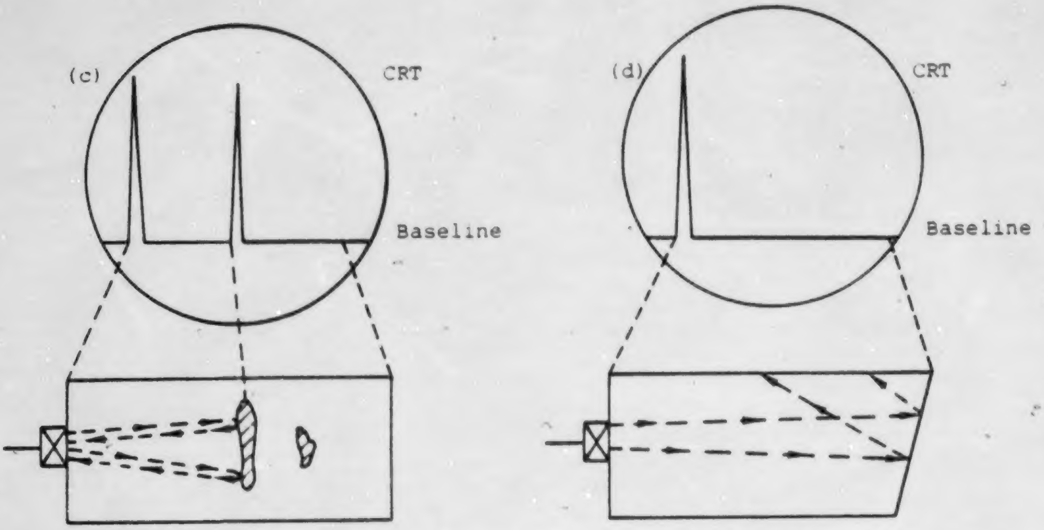
Measurement of the exact size of a flaw is not easily accomplished because the orientation, shape, depth, and nature of the flaw all affect its ability to reflect ultrasound. If a flaw is detected, more procedures may be employed to survey for size and orientation.

Some schematic views of typical A-scan data presentations are given in Figure 32-1-32. Part (a) shows the CRT display for the case of no detectable flaws in the test sample: there are only two peaks, the front surface and backwall echoes. The gap between these two peaks is, again, proportional to the object's thickness. Part (b) of Figure 32-1-32, shows the CRT display corresponding to a small flaw in the test piece. The peak due to the flaw appears in the same position relative to the front surface and backwall peaks that the flaw itself occupies with respect to the two surfaces.


(a)
CRT
Baseline
(b)
CRT
Baseline

(a) No flaw

(b) Small flaw


(c)
CRT
Baseline
(d)
CRT
Baseline

(c) Large flaw - no backwall echo and no echo from the masked flaw.

(d) Inclined backwall, no backwall echo. Same for an inclined flaw.

Figure 32-1-32 Schematic representations of typical A-scan data presentations in the pulse echo method.

Part (c) depicts the masking effect of a flaw larger than the beam and part (d) depicts the loss of signal due to the beam impinging upon an inclined surface. In this case it was the backwall, although it could have been an inclined flaw.

A test sample with parallel faces normal (or perpendicular) to the test beam shields multiple echoes, even without flaws, if the scale is set so that the first backwall echo is not on the right hand half of the screen. The additional echoes are due to multiple reflections off the surfaces of the test sample. The apparent positions of the additional wall can be seen in Figure 32-1-33 below. The heights of the echoes decrease because of an attenuation increase with increased path length and not all the incident beam is reflected at each interface. See Section on reflection and transmission coefficients.

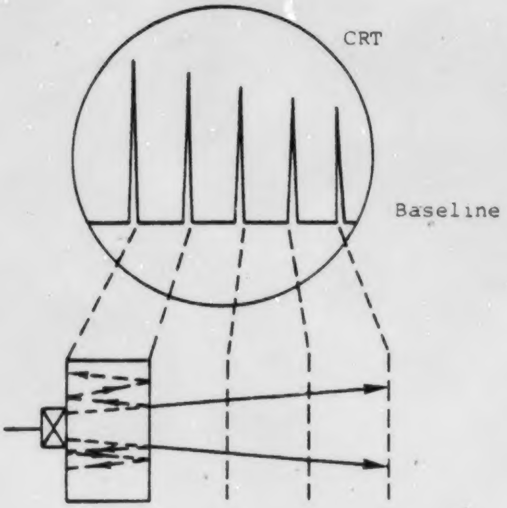


Figure 32-1-33 Multiple Echoes in a Flat Test Piece

The frequency at which these multiple echoes occur is referred to as the echo repetition frequency or the travel frequency and should not be confused with the pulse repetition frequency, which is the rate at which pulses are produced by the probe.

B-Scan

The B-scan version of the pulse-echo method uses the oscilloscope to display the elapsed time (vertically downwards) versus probe position (horizontally) as the probe is mechanically swept across the test piece. The oscilloscope itself will virtually always have a long persistence coating of phosphor to retain parts of the image already formed as the rest is swept out. The horizontal deflection will synchronize with the motion of the probe, which will normally be linear in direction and at constant speed. The intensity of the sweeps is modulated to represent the intensity of the echo, a bright segment indicating a strong echo.

The B-scan will therefore represent a "cross-section" of the tested material. This is the chief value or use of the B-scan. It can scan rapidly for the presence or distribution of flaws in a test piece and the results used to select where to scan more thoroughly using the A-scan method. The B-scan results may be recorded by facsimile or photographic equipment, or have the output data reproduced on an x-y plotter. Figure 32-1-34 shows a typical B-scan schematically.

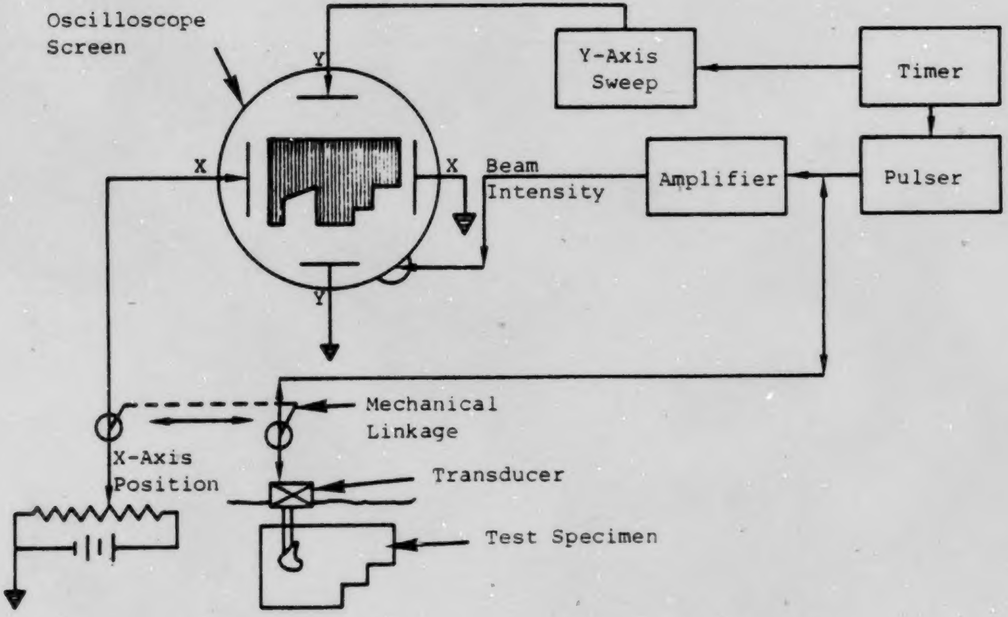

Oscilloscope Screen
Y
X
X
Beam Intensity
Y
Y-Axis Sweep
Timer
Amplifier
Pulser
Mechanical Linkage
X-Axis Position
Transducer
Test Specimen

Figure 32-1-34 Schematic Representation of a B-scan test.

The B-scan "cross section" is generally set up with the top of the display representing the front surface and the bottom representing the backwall.

C-Scan

The C-scan is a two dimensional or planar view of the sample, displaying the positions of any detected discontinuities in the sample but no depth information. The probe is moved over the test sample in some kind of search pattern. The usual pattern is a series of parallel lines although zig zags and spirals are occasionally used. As in the B-scan, mechanical linkages are used to indicate the position of the probe to the x-y plotter.

The most important addition in the C-scan equipment, when compared to the B-scan, is the depth gate. This device allows only discontinuity signals from between two selected depths to be displayed. This allows you to reject the front surface and backwall echoes which would otherwise completely obscure the flaws. Generally, the gate will be set to just barely exclude the front surface and the backwall from the display, but the gate can be used to display a series of sections or slices of the test item, which is the only way to get depth information by C-scan.

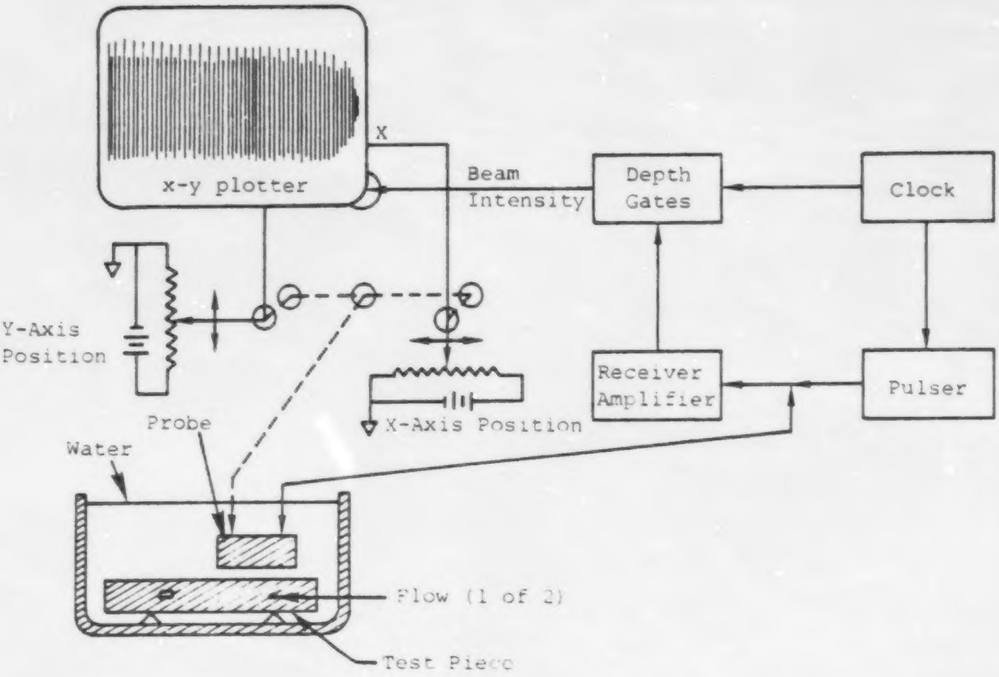

x-y plotter
X
Beam Intensity
Depth Gates
Clock
Y-Axis Position
Receiver Amplifier
Pulser
X-Axis Position
Probe
Water
Flow (1 of 2)
Test Piece

Figure 32-1-35 Schematic Diagram, C-Scan System for Pulse Echo Method

Figure 32-1-35 shows the schematic of a typical C-scan system as discussed above. Figure 32-1-36 shows a typical x-y plot obtained by C-scan with the flaws displayed as the light or blank areas. The opposite case is the flaws displayed as darkened regions. Both methods are common.

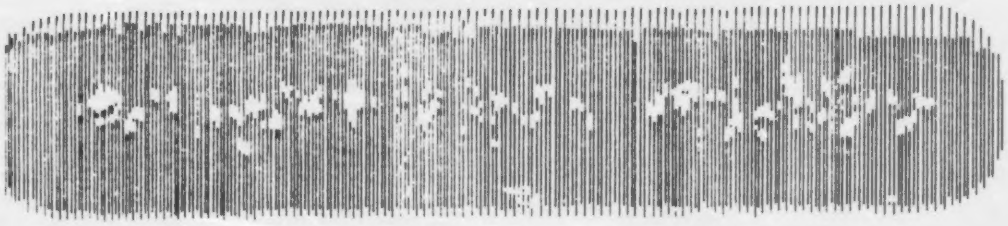


Figure 32-1-36 Typical C-Scan Recording

Transit Time Methods

In actuality, pure transit time methods have already been covered. All one has to do to make an intensity transit time method into a transit time method is to disregard intensity readings. A pulse-echo instrument may be converted to a transit time method merely by replacing the CRT with a digital readout for elapsed time.

The transit time method first used, as early as 1941, was the "sing-around" method. The returning echo triggers a second pulse, thereby making the pulse repetition frequency equal to the echo repetition frequency instead of being preset. The pulse repetition frequency can then be directly measured and the round trip period (T) of a pulse found by solving Eq 32-1-21 for period:

$$T = \frac{1}{f} \qquad \text{Eq 32-1-21}$$

Where:

T = period
f = frequency

The thickness or the depth of a flaw can be given by:

$$d = \frac{c \cdot T}{2} = \frac{c}{2f_r} \qquad \text{Eq 32-1-22}$$

Where:

d = thickness
c = velocity
f_r = pulse repetition frequency

The essential drawback to this method is that the triggering time of a pulse is a very difficult quantity to control, and generally speaking, it isn't as accurate as the pulse-echo method.

EXAMPLE: 1.13

Problem: What is the approximate thickness in inches of a steel plate for a particular pulse repetition frequency.

Given: $f_r = 59$ kHz

Solution: $d = \frac{c}{2f_r} = \frac{5.9 \text{ km/sec}}{2 \times 0.059 \text{ MHz}} = 50\text{mm}$ $\underline{\underline{d = \approx 2 \text{ in.}}}$

EXERCISES

The following exercises reinforce the concepts presented in this module.

1. Perform the Resonance Wall Thickness Method to measure a sample thickness as outlined in the Procedures section of this module.

2. Perform either a wall thickness measurement or a flaw detection by using the Pulse Echo Method as outlined in the Procedures section of this module.

3. Define the following terms:
   a. wavelength
   b. period
   c. frequency
   d. velocity
   e. acoustic impedance
   f. reflection
   g. refraction
   h. longitudinal wave
   i. transverse wave
   j. surface wave

4. Answer the following questions as either true or false:

____ a. The three basic parameters of a wave are its wavelength (λ), frequency (f), and velocity (v). Velocity is equal to the product of wavelength and frequency ($v = \lambda f$).

____ b. Two basic wave modes used in UT are longitudinal and transverse waves. Surface and plate waves are less frequently utilized.

____ c. The angle of reflection equals the angle of incidence ($\theta i = \theta r$), when an ultrasonic wave is reflected from an internal flaw.

____ d. When an ultransonic wave is refracted at an interface, the relationship between the angle of incidence and angle of refraction is given by Boyle's Law.

____ e. When an ultrasonic wave is refracted, the incident wave is split into L-wave and S-wave refracted waves.

____ f. When the critical angle of incidence is passed, total internal refraction occurs.

5. Identify and describe the following components and their functions for a typical ultrasonic test setup: probe, signal generator, receiver, cathode ray tube, amplifier, clock, and power supply.

6. Identify the type and purpose of an ultrasonic test given a schematic diagram of the test setup.

7. Answer the following questions as either true or false:

____ a. The basic components of an ultrasonic test unit are: the power supply, pulser, receiver-amplifier, clock ocsilloscope, and probe (A-Scan setup).

____ b. Transducers are ferromagnetic devices.

____ c. The most common transducer material is quartz followed by lithium sulfate, barium titanate, and lead metaniobate. Quartz is very hard, lithium sulfate the best receiver, barium titanate the best transmitter, and lead metaniobate the best all around except it's soft.

____ d. A couplant, usually a molybdenum-base grease, is used to conduct the sound waves from the transducer to the test piece.

____ e. An x-y plotter is the best means of presenting UT data to a technician.

8. Identify and briefly describe, the test method which would accomplish a stated test requirement.

9. Name the four (4) basic wave modes discussed in this module and describe each.

10. Name the four (4) classes of ultrasonic test and describe each.

11. Name the three (3) types of pulse-echo tests and distinguish between them.

MATERIALS

To carry out Exercise #1 the following materials are required as shown in Figure 32-1-37 of the Procedures.

1. Ultrasonic transducer
2. High frequency generator with variable frequency
3. Signal amplifier
4. Sweep voltage generator
5. Oscilloscope
6. Aluminum plate or sheet whose thickness is to be measured.

To carry out Exercise #2 the following materials are required as shown in Figures 32-1-31 or 32-1-34 of this module.

1. Ultrasonic transducer(s)
2. Oscilloscope
3. Signal amplifier
4. Pulser
5. Timer
6. High frequency pulse generator
7. Steel test specimen with internal flaw
8. Steel test specimen with no internal flaws

PROCEDURES

The following procedures refer to Exercises 1, 2 and 3 of this module.

1. Resonance Wall Thickness Method

   Using the test procedure explained on pages 32-1-44 through 32-1-52, measure the thickness of a sheet of aluminum using the Resonance Wall Thickness method. It is suggested that the measurement be carried out using the transducer and oscilloscope described in this section of the module.

   The following sketch in Figure 32-1-37 shows the basic test set-up for the resonance method for measuring the wall thickness of any material.

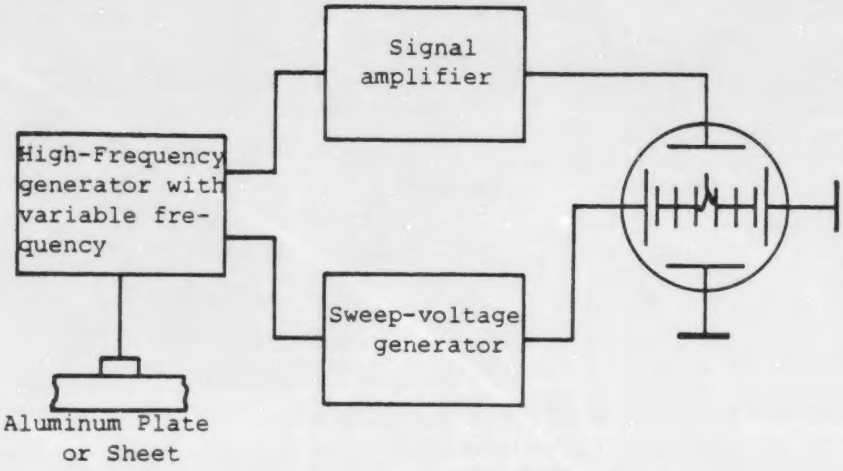

Signal amplifier
High-Frequency generator with variable frequency
Sweep-voltage generator
Aluminum Plate or Sheet

Figure 32-1-37 Test Set-up for Measurement of Wall Thickness through a Material

In the event that such equipment is not available, a field trip to an industrial site in which actual testing of this type is performed can be substituted. A report should be prepared on this aluminum sheet measurement:

a. List Title of Exercise.
b. Describe, very briefly, the method being used.
c. Read the manufacturers instruction manual and construct a block diagram similar to Figure 32-1-37 for the equipment involved.
d. Describe how the equipment is calibrated.
e. Describe the test piece.
f. Make the measurement(s) required to perform the test.
g. Record the results and with diagrams show how the measurement(s) was (were) made.

2. Pulse Echo Method

Using the test procedure outlined on pages 32-1-57 through 32-1-66 measure the wall thickness or the depth of an internal flaw using a test instrument set-up as shown in either Figures 32-1-31 32-1-34 of this module. These tests and measurements should be written up as shown below: with step f included for an actual laboratory or simulation and excluded for a demonstration or a field trip report.

a. List Title of Exercise.
b. Describe very briefly, the method being used.
c. Read the manufacturers instruction manual and construct a block diagram similar to Figure 32-1-31 or Figure 32-1-34 for the equipment involved.
d. Describe how the equipment is calibrated.
e. Describe the test piece.
f. Make the measurement(s) required to perform the test.
g. Record the results and with diagrams show how the measurement(s) was (were) made.

DATA TABLE

Not applicable.

REFERENCE MATERIALS

General Dynamics, Convair Division; *Classroom Training Handbook for Nondestructive Testing: Ultrasonic Testing;* General Dynamics; San Diego, California; 1967.

Goldberg, Barry B., et al; *Diagnostic Uses of Ultrasound*; Grune and Stratton; New York, 1975.

Hueter, T.F. and Bolt, R.H.; Sonics, 5th ed.; ASNT; Columbia, Ohio; 1966.

Krautkrämer, J & H; *Ultrasonic Testing of Materials*; Springer-Verlag; New York; 1969.

Ward, Raymond, et al; *Metals Handbook, 8th Edition*, Volume 11, "Nondestructive Inspection and Quality Control;" American Society for Metals; Metals Park, Ohio, 1976.

Principles of Ultrasonic Wave Behavior

1. The boundary between two materials in contact with each other is called a(n) ____________________.
   - (a) lens
   - (b) interface
   - (c) focuser
   - (d) attenuator

2. The speed of propagation of a wave is also called its ____________________.

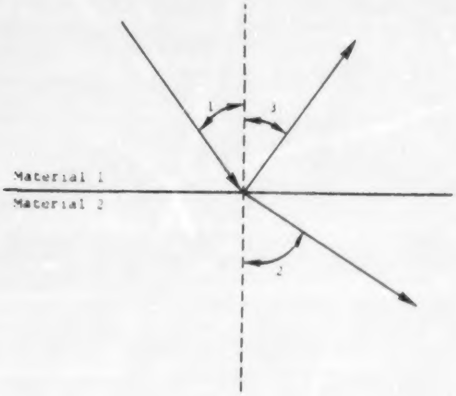


Figure 32-1-A

Questions 3 through 5 refer to these answers:
- (a) angle of incidence
- (b) angle of reflection
- (c) angle of refraction
- (d) none of the above

3. In Figure A angle 1 is called the ____________________.

4. In Figure A angle 2 is called the ____________________.

5. In Figure A angle 3 is called the ____________________.

6. Most ultrasonic testing is done between:
   - (a) 1-25 megahertz
   - (b) 25-100 megahertz
   - (c) 1-25 kilohertz
   - (d) 25-100 kilohertz

7. The formula $\frac{\sin\theta_1}{\sin\theta_2} = \frac{V_1}{V_2}$ is known as:
   - (a) Snell's Law
   - (b) Huygen's Principle
   - (c) Phase conversion formula
   - (d) Impedence Formula

8. In Figure A, assuming no mode conversion, which two angles are always equal?
   - (a) Angles 1 and 3
   - (b) Angles 2 and 3
   - (c) None of these

9. The velocity of sound is highest in:
   - (a) aluminum
   - (b) air
   - (c) water
   - (d) steel

10. The point in a wave pattern where destructive interference cancels all apparent wave motion is called a:
    - (a) compression
    - (b) rarefaction
    - (c) antinode
    - (d) node

11. The product of ____________________ and ____________________ equals the velocity of a wave.

12. What is the wavelength of:
    - (a) a 1 MHz longitudinal wave in aluminum?
    - (b) a 5 MHz transverse wave in steel?

13. An longitudinal ultrasonic wave in water is incident upon steel at 10°, and is partly transmitted with mode conversion. What is the:
    - (a) angle of reflection?
    - (b) angle of refraction for the L-wave?
    - (c) angle of refraction for the S-wave?

14. For a 2 MHz signal in steel, with a 1/2 in. transducer, what is the length of the near field and at what half angle does the far field spread?

15. Sketch the rays in problem 13, showing the correct angles approximately.

16. A material used between a probe and the test material to improve the transmission of ultrasonic waves is called the ______________.
    - (a) wetting agent
    - (b) damping block
    - (c) crystal
    - (d) couplant

17. The piezoelectric material in a probe or search unit is called the ______________.
    - (l) housing
    - (b) damping block
    - (c) crystal
    - (d) couplant

18. A scale electronically imposed on the screen of a CRT in a test unit to permit rapid measurement of distance may be referred to as ____________.

(a) baseline
(b) pip
(c) sweep
(d) marker

19. A disadvantage of using a quartz probe is that it ________________.

(a) will dissolve in water
(b) is an inefficient ultrasonic generator
(c) wears quickly
(d) needs special couplants

20. On many test instruments, while conducting an immersion test, it is possible to remove the portion of the pattern representing water by adjusting the __________.

(a) pulse length control
(b) reject control
(c) sweep delay control
(d) sweep length control

21. The transducer most frequently found in ultrasonic probes utilize _______________.

(a) magnetostrictive principles
(b) piezoelectric principles
(c) mode conversion principles
(d) none of the above

22. Which material is the best ultrasonic transmitter?
- (a) lithium sulfate
- (b) barium titantate
- (c) quartz
- (d) silver oxide

23. Which material is the best ultrasonic receiver?
- (a) lithium sulfate
- (b) barium titanate
- (c) quartz
- (d) silver oxide

24. Which material wears best?
- (a) lithium sulfate
- (b) barium titanate
- (c) quartz
- (d) silver oxide

25. In the typical instrument described in this section, the clock controls the _______________.
- (a) pulse length
- (b) amplification
- (c) pulse repetition rate
- (d) sweep length

26. Identify and describe the purpose of each of the six major components of an ultrasonic test assembly.

27. How thick must a quartz plate be to oscillate most efficiently at 15 MHz?

28. Describe the difference(s) between video and RF modes.

29. State the three (3) basic purposes that damping blocks fulfill in a transducer.

30. The vertical deflection on a test instrument CRT is driven by the output of the _______________. The horizontal by the output of _______________.

31. A form of thickness measurement testing in which ultrasonic vibrations of varying frequency are introduced into the test piece is called:
(a) pulse echo method
(b) intensity method
(c) resonance method
(d) immersion testing

32. In resonance testing, the resonant peaks may be obtained at either the fundamental frequency or at _______________ which are the upper harmonics.
(a) multiple reflections
(b) overtones
(c) nodes
(d) anti-nodes

33. In ______________ ultrasonic waves are transmitted into the test sample as short and repetitive wave packets.
   (a) pulse echo testing
   (b) continuous wave testing
   (c) resonance testing
   (d) all of the above

34. In Figure 32-1-B, showing a typical resonance device display, what thickness is indicated?
   (a) 7.00mm
   (b) 1.75mm
   (c) 8.00mm
   (d) 5.25mm

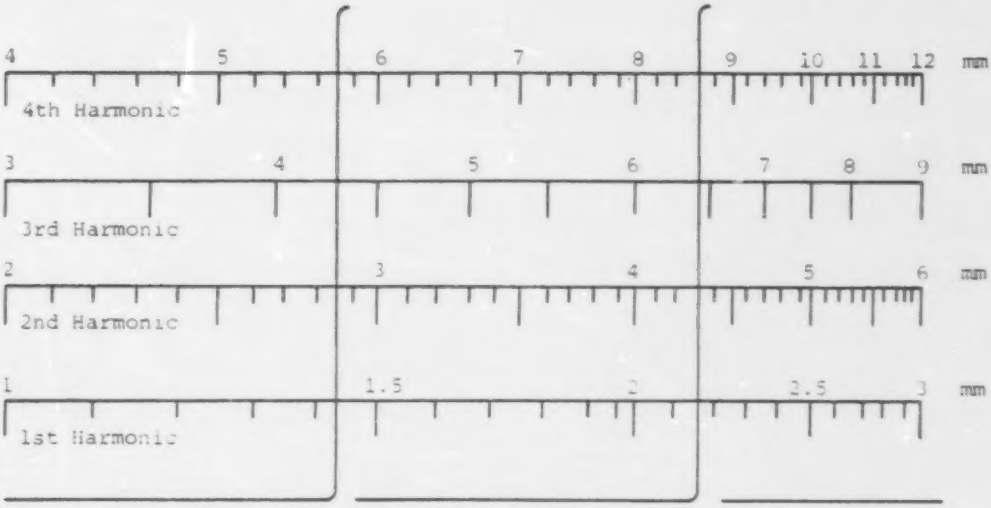

4 5 6 7 8 9 10 11 12 mm
4th Harmonic
3 4 5 6 7 8 9 mm
3rd Harmonic
2 3 4 5 6 mm
2nd Harmonic
1 1.5 2 2.5 3 mm
1st Harmonic

Figure 32-1-B

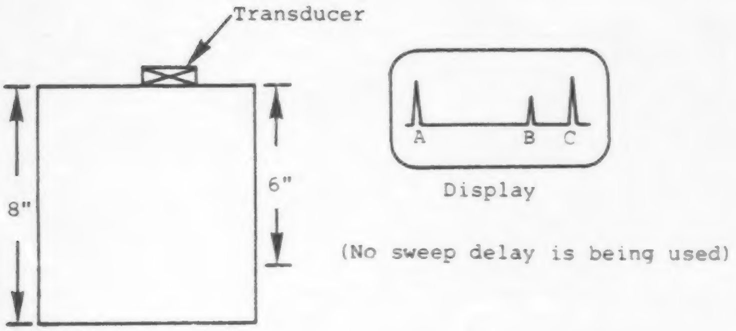

Transducer
8"
6"
A
B
C
Display
(No sweep delay is being used)

Figure 32-1-C

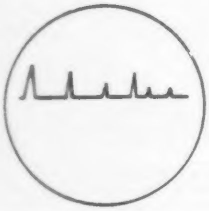


Figure 32-1-D

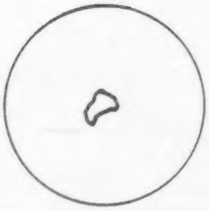


Figure 32-1-E

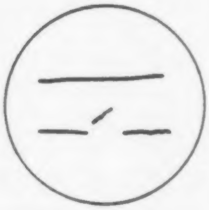


Figure 32-1-F

35. In Figure 32-1-C, what does display peak A represent?

- (a) front surface
- (b) flaw
- (c) backwall
- (d) none of the above

36. In Figure 32-1-C, what does display peak B represent?

- (a) front surface
- (b) flaw
- (c) backwall
- (d) none of the above

37. In Figure 32-1-C, what does display peak C represent?

- (a) first backwall reflection
- (b) second backwall reflection
- (c) first flaw reflection
- (d) second flaw reflection

38. Figure 32-1-D is a typical ______________.

- (a) A-scan
- (b) B-scan
- (c) C-scan
- (d) D-scan

39. Figure 32-1-E is a typical ______________.

- (a) A-scan
- (b) B-scan
- (c) C-scan
- (d) D-scan

40. Figure 32-1-F is a typical ______________.

- (a) A-scan
- (b) B-scan
- (c) C-scan
- (d) D-scan

41. List the four types of methods of ultrasonic testing discussed and state which type(s) can be used to determine:
    - (a) wall thickness
    - (b) flaw presence
    - (c) flaw location

42. List the four types of intensity method testing and distinguish between them on the basis of sound transmission.

43. List the three display schemes in pulse-echo testing and for each list the variables or quantities displayed on the axes of the display.

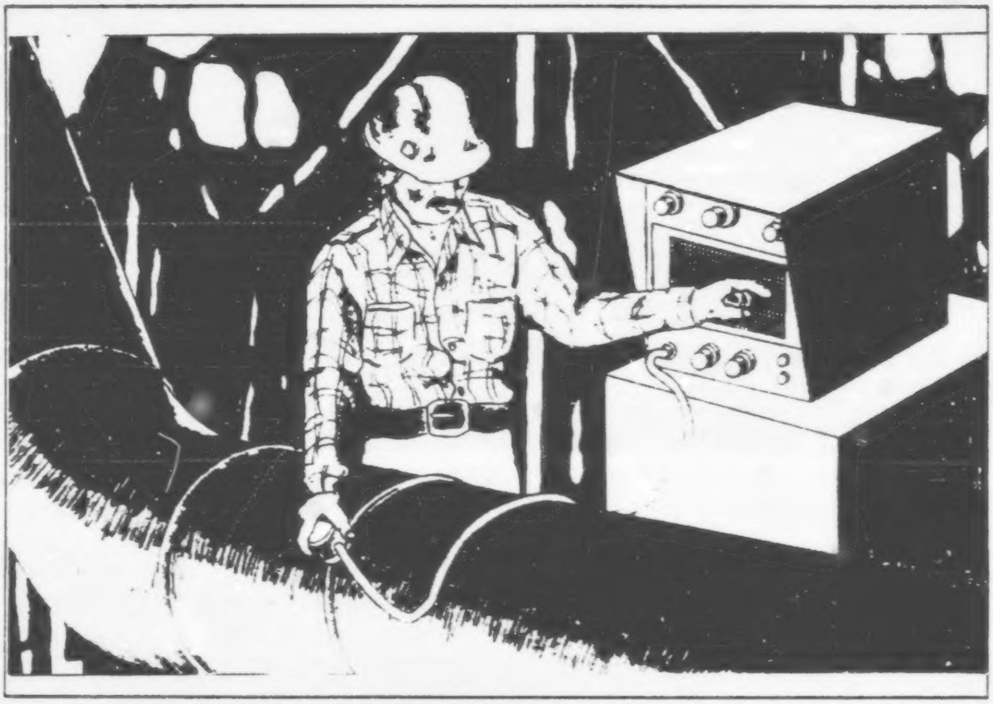
44. State the reason that requires reflection intensity testing to use two probes.

45. Distinguish between phosphor coatings on CRT's in A-scan and B-scan instruments.

NUCLEAR TECHNOLOGY

MODULE 32 - 2

OPERATION OF ULTRASONIC TEST EQUIPMENT



COURSE 32: NONDESTRUCTIVE EXAMINATION (NDE)

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

MODULE 32-1	Fundamentals of Ultrasonic Testing
⇨ MODULE 32-2	Operation of Ultrasonic Test Equipment
MODULE 32-3	Fundamentals of Magnetic Particle Testing
MODULE 32-4	Operation of Magnetic Particle Test Equipment
MODULE 32-5	Fundamentals of Eddy Current Testing
MODULE 32-6	Operation of Eddy Current Test Equipment

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INTRODUCTION

The Nuclear QA/QC Technician may have several responsibilities for ultrasonic examinations. The technician may serve as an ultrasonic test inspector. Also, the technician may assist in reviews and audits of ultrasonic test reports and practices by other organizations.

Ultrasonic testing is widely used in the nuclear industry. It is a volumetric test which examines the volume of materials and welds. It is mostly used for the examination of base metals by material fabricators and for in-service inspections of welds by the nuclear power plant operator. In these uses, the pulse-echo method is used almost without exception. Both contact and immersion techniques are used. A-scan is mostly used with contact method and A-scan or C-scan is used with immersion method. This module describes specific ultrasonic test techniques and calibration principles associated with these tests.

MODULE PREREQUISITES

The student/trainee should have prior training or experience in fundamentals of ultrasonic testing. Completion of Nuclear Technology Module 32-1, Fundamentals of Ultrasonic Testing, satisfies this prerequisite.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Compare single and double transducers.
2. Differentiate longitudinal and shear wave techniques.
3. Calculate critical angles and angles of incidence with respect to angle beam testing.
4. Plot angle beam scanning paths for given test specimens.
5. Describe the surface wave technique.
6. Differentiate contact and immersion techniques.
7. Briefly describe squirter, bubbler, and wheel techniques.
8. Discuss the factors associated with selection of search units.
9. Recognize ASME, ASTM, and IIW calibration reference blocks.
10. Describe and perform linearity calibration.
11. Describe and perform sweep range calibration.
12. Describe and perform distance amplitude calibration.
13. Relate minimum detectable flow size and test frequency.
14. Describe and demonstrate techniques for determining flow position, depth and size.
15. Describe effects of grain size and acoustic velocity variables on ultrasonic testing.

ULTRASONIC TEST TECHNIQUES

Types of Techniques

There are four classes of methods available to the ultrasonic technician. Of these, there is one class that is widely used. This is the intensity and transit time (ITT) method. The most commonly required type of ITT method by governing codes is the pulse-echo method.

The pulse-echo method is generally conducted by two means: contact testing and immersion testing. In most contact tests the probes are generally hand held and manually swept over the search area. A couplant is virtually always required. Immersion testing is generally automated and typically uses water, oil, or glycerin as couplant.

Two general categories of contact testing exist: straight beam testing and angle beam testing. Straight beam testing uses longitudinal waves whereas angle beam testing uses shear waves (transverse waves). When the shape of the test piece prevents straight access to the region or volume of interest, the angle beam method, is used. Angle beam transverse testing is also the type used to produce surface waves at the S-wave critical angle.

Straight Beam Contact Techniques

Pulse-echo contact testing using straight beams typically employs the A-scan method. Single or double transducers may be used. The single transducer technique is most useful when testing smooth parallel surfaces. The double transducer or pitch-catch technique is useful for a rough or inclined back surface. Another use for the double transducer method is to isolate electrically the pulser and receiver-amplifier. This prevents the pulser from saturating the receiver-amplifier with the transmitted pulse, thereby avoiding the dead or recovery time after that initial pulse. This improves the resolution of the instrument with respect to discontinuities near the surface of the test piece.

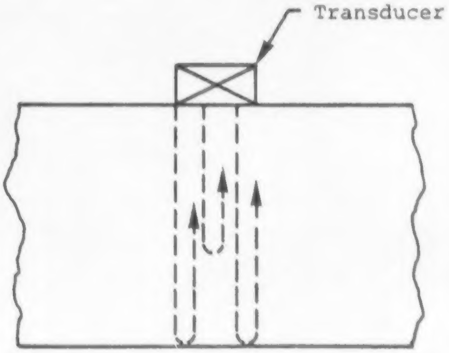


Figure 32-2-1 Single-Transducer Technique

If two transducers are used in the examination of a test piece, one additional advantage accrues to the examiner. The transmitting and receiving transducers may be constructed of different materials that closely match the function of each transducer. For example, the transmitter might be composed of barium titanate and the receiver of lithium sulfate.

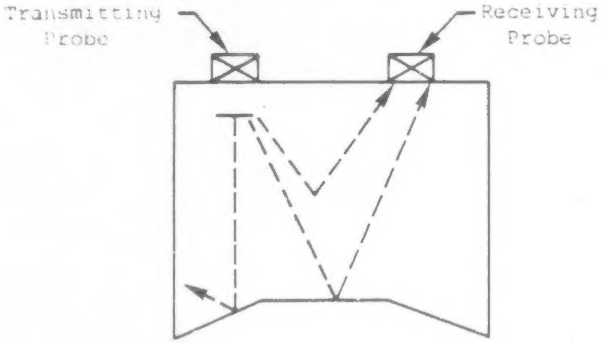


Figure 32-2-2 Double-Transducer or Pitch-Catch Technique

Angle Beam Technique

The angle-beam contact technique is used to transmit ultrasonic transverse waves into the test sample. Since it is desirable to avoid mixed modes, this technique almost invariably uses transverse or shear waves with a contact angle between the first and second critical angles. This will cause the longitudinal waves to be totally reflected at the interface and only the transverse waves are propagaged in the test piece.

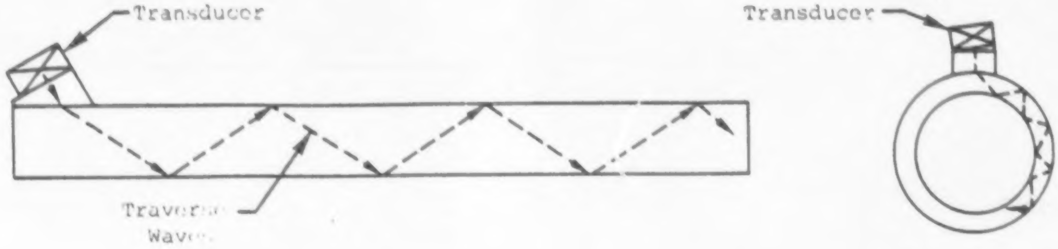


Figure 32-2-3 Angle Beam Techniques

The contact angle is obtained by use of a rigid, wedge-shaped adaptor. In order to operate between the critical angles it is necessary to have a material for the wedge with a lower velocity of sound than in the test substance. And since there is mode conversion, the longitudinal velocity in the adaptor must be smaller than the transverse velocity in the test substance. When testing aluminum or steel, therefore, a longitudinal velocity of less than $3000 \frac{m}{sec}$ or $3 \frac{km}{sec}$ is highly desirable in the adaptor. Lucite, with $C_1 = 2.7 \frac{km}{sec}$, is ideal.

EXAMPLE: 32-2-1

Problem: What are the two critical angles for a lucite to steel interface?

Given: steel: $C_1 = 5.9 \frac{\text{km}}{\text{sec}}$ $C_t = 3.2 \frac{\text{km}}{\text{sec}}$

Lucite: $C_1 = 2.7 \frac{\text{km}}{\text{sec}}$

Solution: $\Theta c_1 = \sin^{-1} \frac{C_{1p}}{C_{1st}} = \sin^{-1} 0.46 = \underline{\underline{27^\circ}}$

$\Theta c_2 = \sin^{-1} \frac{C_{1p}}{C_{1st}} = \sin^{-1} 0.84 = \underline{\underline{57^\circ}}$

EXAMPLE: 32-2-2

Problem: What angle of incidence in lucite produces a 45° angle in steel for transverse waves?

Given: ($C_e = 2.7 \frac{\text{km}}{\text{sec}}$) lucite, ($C_t = 3.2 \frac{\text{km}}{\text{sec}}$) steel

Solution: $\frac{\sin \Theta_1}{\sin \Theta_{st}} = \frac{C_1}{C_{st}}$

$\sin \Theta_1 = (\frac{2.7}{3.2}) \sin 45^\circ = 0.84 \times 0.71 = 0.60$

$\Theta_1 = 36.6 \approx 37^\circ$

Angle probes with lucite adaptors are pre-calibrated for the angle of refraction into steel. Care should be taken to account for the change of angles due to different sound velocities in other materials, such as aluminum or copper.

When locating a flaw or discontinuity by the angle beam method, one must normally examine some particular plane of interest in the sample. To complete such an examination, the transducer must be moved from the distance 2L to the distance L from the plane of interest. This will permit the beam to transverse the plane completely, as can be seen in Figure 32-2-4. The distance 2L is referred to as the skip distance or a V-path length.

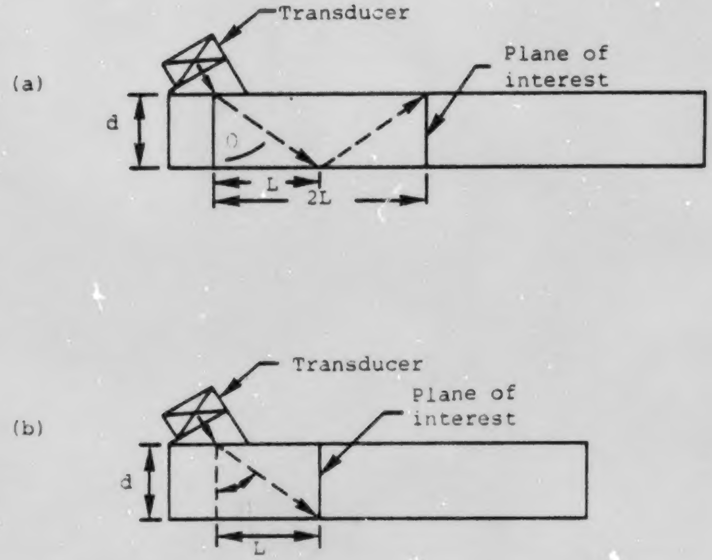


Figure 32-2-4 Angle Beam Technique

By simple trigonometry L can be computed, given d and θ:

$$L = d \tan \theta \qquad \text{Equation 32-2-1}$$

Where

L - ½ skip distance
d = test material thickness
θ = entry angle

In addition to checking the thickness direction of the test piece, the test pattern must sweep the width of the test piece. These two patterns can be combined to produce a zig-zag search or scanning pattern as shown in Figure 32-2-5. The boundary marks for the scanning pattern are established by the value of L as calculated by equation 32-2-1. The boundary marks and scanning pattern assure coverage of the entire weld volume by the angle beam technique.

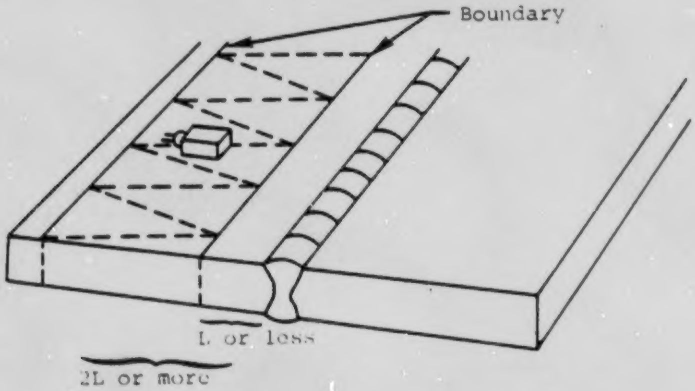


Figure 32-2-5 Scanning Path for Angle Beam Examination of a Weld

Surface Wave Contact Technique

A special case of angle beam testing occurs when the angle of incidence equals the second (or S-wave) critical angle. The mode conversion to transverse waves at the interface then produces surface or Rayleigh waves which then propagate along the surface. These surface waves will follow the surface around the curves, excepting, of course, sharp corners. The surface wave technique is most useful in locating flaws which extend to the surface or are in the dead-zone or near-field for other techniques. Figure 32-2-6 shows an example of surface wave technique

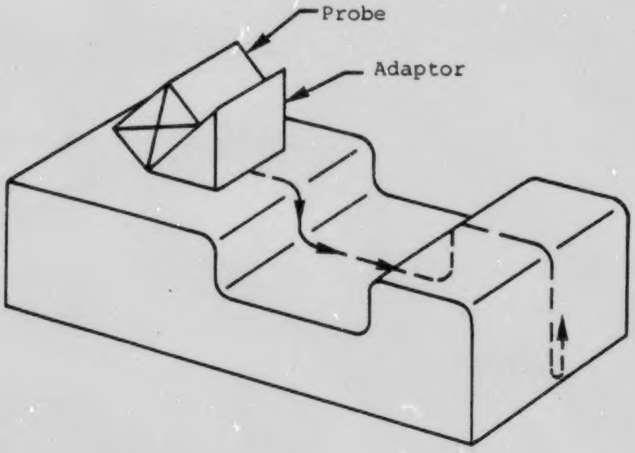


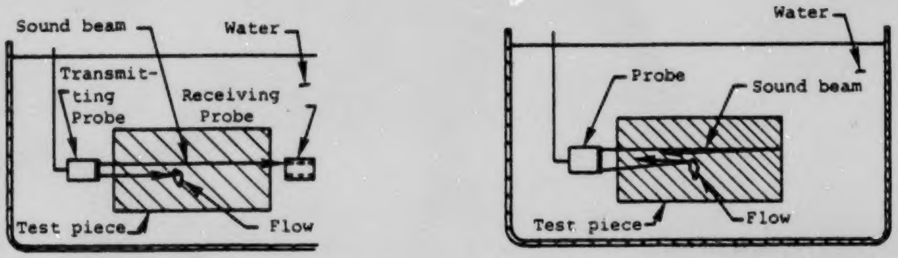
Figure 32-2-6 Surface-Wave Technique

Immersion Testing

The immersion method of ultrasonic testing consists of three basic techniques: the immersed technique where both the transducer and the test specimen are under couplant; the bubbler or squirter technique where the ultrasound is transmitted in a column of flowing water; and the wheel scanning technique where the transducer is immersed in a water-filled rubber tire. As in contact testing, the pulse-echo method is most commonly used.

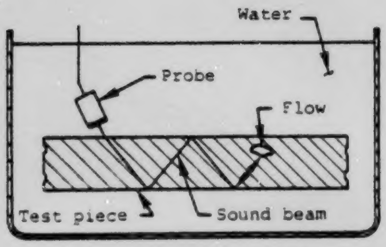
Immersed Technique

In the immersed or conventional immersion technique, both the probe and the test piece are immersed in couplant. Water is frequently used as the couplant for this technique. Immersion probes are essentially waterproof straight beam units with angle-beam inspection being accomplished by merely changing the position of the probe to various angles with respect to the front surface of the test part. Such a procedure is referred to as angulation.


Sound beam
Water
Transmit-ting Probe
Receiving Probe
Test piece
Flow
Water
Probe
Sound beam
Test piece
Flow

(a) Transmission Testing

(b) Pulse echo with straight beam


Water
Probe
Flow
Test piece
Sound beam

(c) Pulse echo with angled beam

Figure 32-2-7 Conventional Immersion Techniques

As a rule, the conventional immersion technique is accomplished by automated or semi-automated mechanical scanning, as opposed to the manual scanning used in contact testing. Since the various bridge-manipulators in use allow for controlled planar scanning, the conventional immersion technique using an X-Y plotter is the preferred method for C-scans. A typical universal immersion scanner is shown in Figure 32-2-8.

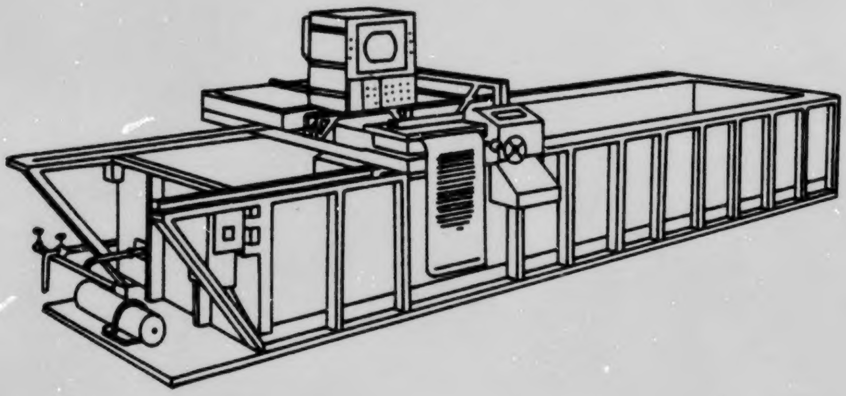
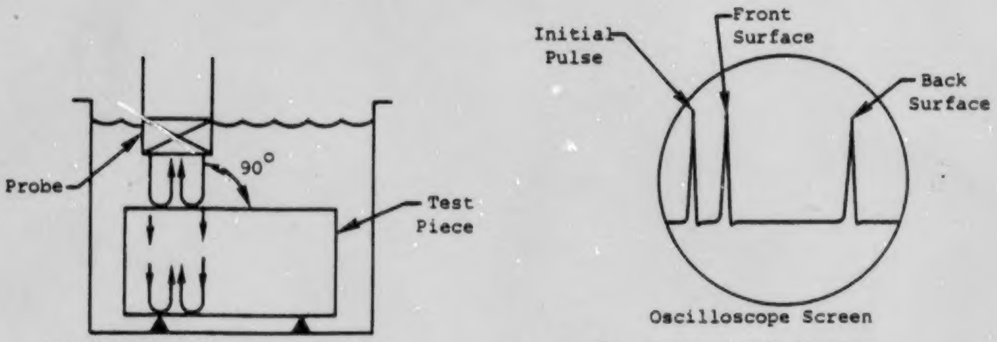


Figure 32-2-8 Sample Immersion Test Equipment

In the immersed technique, there are one or more extra echoes on an A-scan presentation, in addition to the initial pulse. These additional echoes are due to multiple front surface and probe reflections. To eliminate multiple front surface echoes, the acoustical path length in the water. should take longer to traverse than the acoustical path length in the test piece.

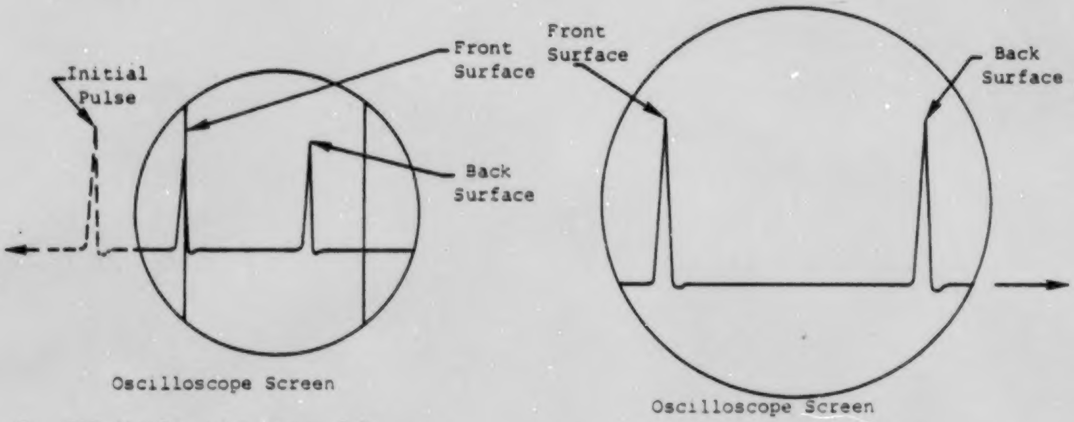
To ensure that this is the case, it is necessary to compare the velocity of sound in water to that of the test piece, which may be typically steel or aluminum. The velocity of sound in steel or aluminum is more than four times the velocity of sound in water. Therefore a water path length of one-fourth the thickness of the steel or aluminum test piece is adequate. As a result, a widely used "rule-of-thumb" has been established in this regard which cites that: *The water thickness employed for the immersed technique shall be one-fourth of the specimen thickness plus a quarter of an inch.*

The A-scan immersion test is illustrated in Figure 32-2-9.


Probe
90°
Test Piece
Initial Pulse
Front Surface
Back Surface
Oscilloscope Screen

(a) Straight-beam, pulse-echo immersion test set-up

(b) Initial CRT display


Initial Pulse
Front Surface
Back Surface
Oscilloscope Screen
Front Surface
Back Surface
Oscilloscope Screen

(c) CRT display with sweep delay correction to disregard the water path length.

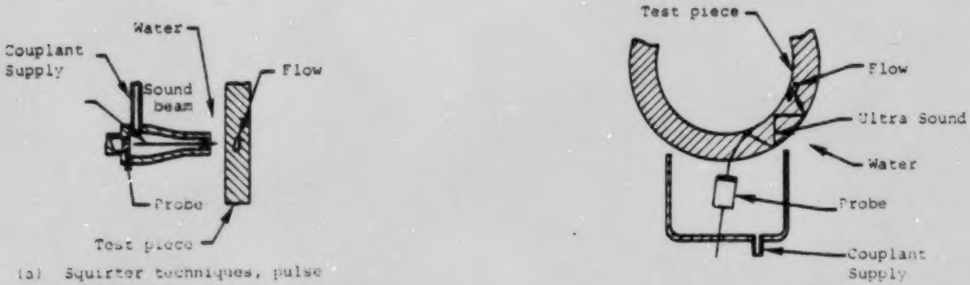
(d) CRT display with sweep correction to display thickness over full scale.

Figure 32-2-9 Straight Beam, Pulse-Echo, Immersion Test

Because the thickness of the test piece is represented by the spacing between the front surface and back wall echoes, the front surface echo should be placed at the left-hand index using the sweep delay control. The initial pulse should now be off screen. Once that has been accomplished, the sweep control can be used to position the back wall echo to the right-hand most index marker as in Figure 32-2-9(d). This last step and succeeding steps are similar to the contact pulse echo method discussed in the proceeding module and in greater detail later in this module.

Water-Column Technique

The water-column technique is known as either the bubbler or the squirter method, depending on the shape and size of the water column. In the squirter technique, Figure 32-2-10(a), the water column gives a more directional flow of the coupling liquid than the bubbler technique, Figure 32-2-10(b).



(a) Squirter techniques, pulse echo method.

(b) Bubbler Technique, pulse echo method

Figure 32-2-10 Basic Water-Column Techniques

The water column techniques can be used as both straight and angle-beam techniques; only the orientation of the probe needs to be changed. The squirter technique can be used as a thorough-transmission technique by using a second squirter assembly on the back surface with a receiving transducer. Water-column techniques are used when the size or shape of a test piece does not lend itself to a submersion in a conventional test tank. As a general rule, large but regularly-shaped test pieces are examined by a squirter technique, while irregularly shaped test pieces are examined by a bubbler assembly.

Wheel Techniques

Wheel techniques are classified as immersion techniques even though the test pieces never get wet. An immersion probe is mounted inside a liquid-filled wheel and the ultrasound travels to the test piece through the liquid. The wheel type probe may also be used for straight or angle-beam testing, and frequently the only adjustment necessary is to tilt the mounting frame.

Wheel type units may be manipulated across the test piece, or held fixed as the test piece is drawn past it. Figure 32-2-11 shows schematic details of wheel-probe operations.

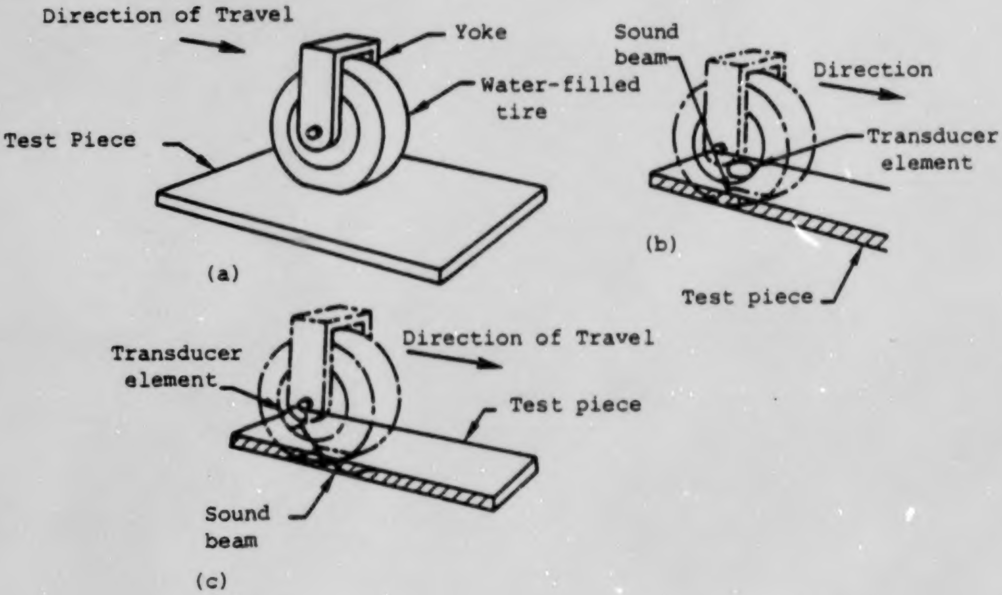

Direction of Travel
Yoke
Water-filled tire
Test Piece
(a)
Sound beam
Direction
Transducer element
(b)
Test piece
Transducer element
Direction of Travel
Test piece
Sound beam
(c)

Figure 32-2-11 Immersion Testing by Wheel Probe

TYPICAL TEST TECHNIQUES AND RESULT INTERPRETATION

This section of the module describes specific techniques of ultrasonic testing and how to interpret the results obtained. Since virtually all nuclear ultrasonic examination is specified to be done by the pulse-echo method, all tests discussed below are pulse-echo techniques.

Probes and Probe Section

When undertaking a pulse-echo examination of a test piece, the optimum test parameters are determined by the configuration and composition of the material. These parameters include type (angle or straight) of test, frequency, coupling conditions, and temperature.

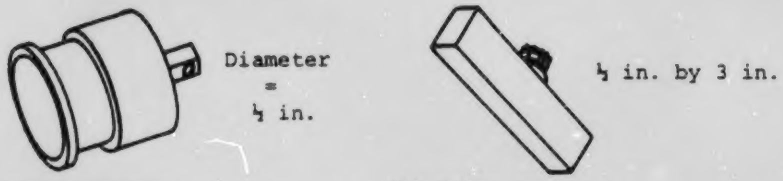
In nuclear NDE testing, the applicable written test procedure dictates straight-beam or angle-beam, and if angle-beam, it generally requires the effective angle in steel to be 45°, although 60° is sometimes required. The type of the technique, which is predetermined for the technician, determines the type of probe to be used.

Today, most angle beam probes are supplied as separate transducer and adapter wedges. The reason is to reduce the cost of probes. As a result, a single transducer can be mated to any of several adaptors. Also, as adaptors wear out, it is much cheaper to replace the adaptor than an entire encapsulated search unit.

Four decisions about the probe must be made: frequency, size of probe, operating temperature, and shape or curvature of the face of the probe.

The optimum frequency for examination is selected by balancing the reduction of attenuation as frequency is reduced against the accompanying reduction of echo amplitude from small flaws. While there exist analytical formulae to determine the optimum frequency, in practice it will be specified for a technician in the written procedure for each test. The transducers have their sensitive frequencies marked on their housing, or in some cases they will be color coded. The technician selects a probe with its sensitive frequency equal to the frequency specified in the UT procedure.

The size of the probe is selected to satisfy requirements of beam divergence, flaw detection versus location, and scanning speed. The larger the beam, the more slowly it diverges, which is important in thicker samples. A very wide beam can be used to detect a flaw and a much smaller beam used to accurately localize it. The term usually applied to a wide type of probe is "paint brush", and a typical set of measurements for a paint-brush probe is 3 inches wide by ½ inch thick. See Figure 32-2-12 for a sketch of a paintbrush transducer.



(a) Normal contact transducer

(b) Paint brush transducer

Figure 32-2-12 Contact Transducers

Temperature selection is a rare issue for the nuclear QA technician. Normally, tests are run at room temperature or at least well within the temperature range of normal probes. If normal probes will not satisfy an inspection procedure because of temperature, then care must be taken to select a high temperature couplant to match the high temperature probe(s).

Couplants

Two factors are very important in selecting and using couplants. First, commercial couplants are available in regular or high temperature versions from most vendors. Most test situations permit use of regular versions, but where high temperature testing is performed, the high temperature version should be selected. Second, when a modular angle-beam probe is used, the interface between the transducer and the adaptor needs a couplant in addition to the couplant between the adaptor wedge and the material surface.

Calibration

Once the probe has been selected for the given procedure, the equipment must then be calibrated. This calibration allows the vendor and owner to achieve comparable results from similar tests, and provides a standard to be utilized in estimating flaw size.

Reference Blocks

Reference blocks are used to calibrate ultrasonic test equipment. Three blocks must meet the requirements of the specific code or standard which applies to the UT examination procedure. The calibration blocks may be fabricated from extensions or cutouts of the material to be examined or they may be standard blocks fabricated from acoustically equivalent material as that to be examined. In either case, the applicable code or standard specifies the characteristics of the calibration block. Applicable codes and standards include those sponsored by American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM), International Institute of Welding (IIW), and American Welding Society (AWS).

All calibration blocks provide ultrasonic reflectors of known size and location. Calibration of the UT equipment is accomplished by adjusting and electric controls on the control unit to obtain proper display of the reflectors in the calibration block. Several types of calibration blocks are reviewed in subsequent paragraphs; later in this module, sample calibration procedures are described.

The ASTM standard reference blocks come in three types of sets: a distance/amplitude set, an area/amplitude set, and a mixed set combining both of the above sets.

The ASTM distance/amplitude blocks provide a standard or reference flaw of a specific size at several depths in the test material. The flaws are flat-bottomed, drilled holes centered in the bottom of the blocks. All the blocks are two inches in diameter, and all the holes are three-quarters of an inch in depth. As illustrated in Figure 32-2-13(a) the hole diameter is fixed at one of three diameters and only the test metal distance varies among the blocks of a set. Thus, these blocks provide a constant size reflector at various, known test metal distances.

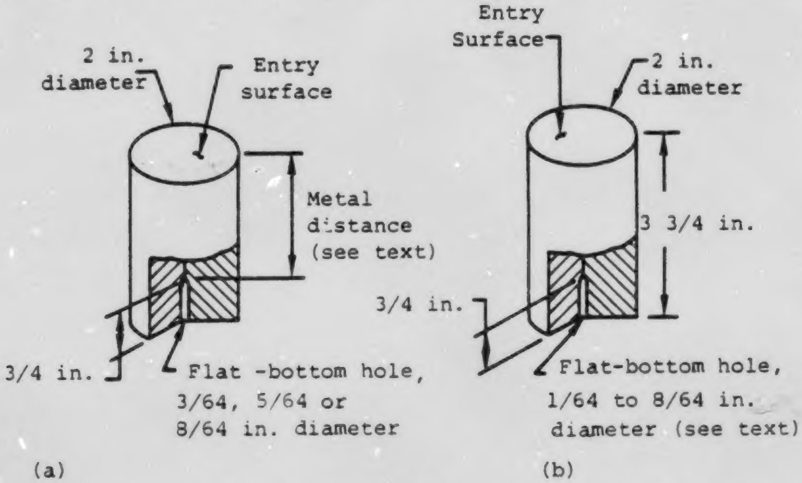

2 in. diameter
Entry surface
Metal distance (see text)
3/4 in.
Flat -bottom hole, 3/64, 5/64 or 8/64 in. diameter
(a)
Entry Surface
2 in. diameter
3 3/4 in.
3/4 in.
Flat-bottom hole, 1/64 to 8/64 in. diameter (see text)
(b)

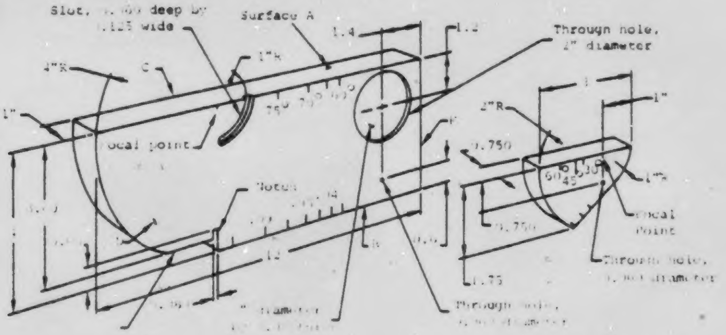
Figure 32-2-13 Standard reference blocks for use in straight-beam ultrasonic inspection: (a) distance-amplitude block and (b) area-amplitude block

The ASTM area/amplitude blocks provide a standard on reference depth of flaw, with the flaws being of various sizes or diameters. As illustrated in Figure 32-2-13(b), the flaws are, again, flat-bottomed holes drilled in the bottom of the blocks and centered. The blocks are, again, two inches in diameter with the bottom holes being three-quarters of an inch long. The metal distance is constant in this case, while the diameters of the hole of flaw differ. Thus, a set of area/amplitude blocks provides various, known flaw sizes at a fixed test metal distance.

Each of the area/amplitude and distance/amplitude blocks is identified by a five digit code number in the form of a single digit separated from four more digits by a dash. The first digit gives the diameter of the hole in sixty-fourths of an inch. The four remaining digits give the metal distance in hundredths of an inch. For example, a block marked 5-0600 has a flat bottomed hole diameter of five sixty-fourths (5/64) of an inch and a metal distance of 600 hundreths of an inch or six inches.

Because a flat-bottomed hole is a specular reflector, it will return an echo that is quite strong. Therefore, any equivalent strength echo from a real flaw will indicate a flaw cross-section larger than the flat-bottomed hole.

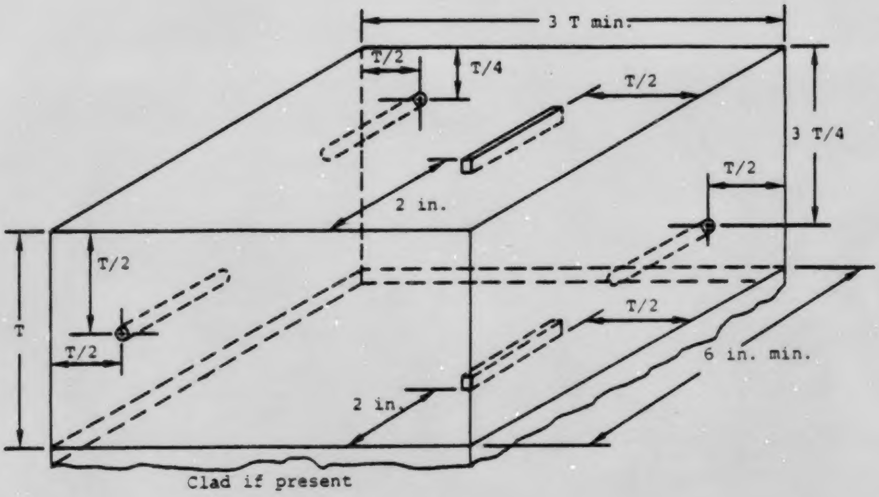
IIW -type blocks are used to calibrate equipment for either longitudinal or transverse (shear) examination and also to check the performance characteristics of an angle-beam search unit such as beam exit or index point and angle of refraction. IIW blocks come in both metric and English dimensions. Typical measurements are 12 in. x 4 in. x 1 in. Figure 32-2-14 shows a typical IIW standard block and an AWS miniature angle-beam block.


Slot, deep by
.125 wide
Surface A
1.4
1.2
Through hole,
2" diameter
4"R
C
1"R
1"
75°
70°
60°
Focal point
Notch
12
2"R
0.750
1"
60
45
30
Focal
Point
Through hole,
diameter
1.75
Through hole,
diameter
diameter

(b) Miniature angle-beam block

Figure 32-2-14 Two standard reference blocks used in ultrasonic inspection: (a) International Institute of Welding (IIW), type 1, block; (b) miniature angle-beam block

The ASME basic calibration block for ultrasonic examination of welds is illustrated in Figure 32-2-15. Side drilled holes are located at ¼T, ½T and 3/4T depths where T equals thickness of the block. Block thickness is equal or close to weld metal thickness as indicated by Figure 32-2-15. Drilled hole diameter is based on weld metal thickness range. Notches are machined to serve as a reflector which simulates flow on the inside surface of the weld.



Weld Thickness(t)	Basic Calibration Block Thickness(T)	Hole Diameter	Notch Size:
1 in. or Less	3/4 in. or t	3/32 in.	Width = 1/8 in. to 1/4 in.
Over 1 in. through 2 in.	1-1/2 in. or t	1/8 in.	
Over 2 in. through 4 in.	3 in. or t	3/16 in.	Depth = 2% T
Over 4 in. through 6 in.	5 in. or t	1/4 in.	
Over 6 in. through 8 in.	7 in. or t	5/16 in.	Length = 2 in. min.
Over 8 in. through 10 in.	9 in. or t	3/8 in.	

Figure 32-2-15 ASME Basic Calibration Block

Test Equipment Calibration

Ultrasonic test equipment is calibrated as a complete system. That is, the control unit, search unit, and cables form the test systems which is calibrated. Typically, three calibrations are required: (1) linearity, (2) sweep range calibration, and (3) distance amplitude. The Procedures section of this module gives specific procedures for performing these calibrations.

Linearity calibration determines the faithfulness of amplitude display on the CRT against either sensitivity (gain) settings or flow sizes. For example, if the sensitivity setting is changed to double the gain, the displayed pulse height should double. Likewise, a flaw signal twice as strong as another flaw signal should give a pulse height twice the amplitude of the other. The ASTM area/amplitude blocks provide a means of determining system linearity. It is recalled that the variable in these blocks is the diameter of the flat bottomed holes. Using the straight beam technique, the displayed pulse height should correlate with cross-sectional area of the holes. The plot of Figure 32-2-16 characterizes system linearity and a given sensitivity setting.

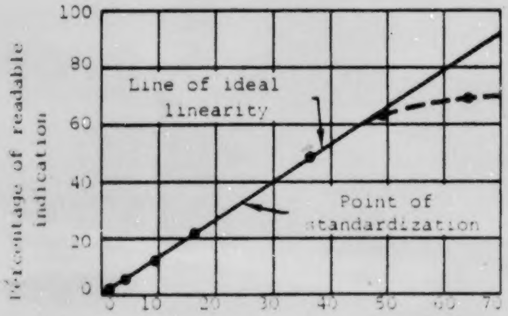


Figure 32-2-16 Typical area-amplitude response curve from test blocks

Sweep range calibration establishes the relationship between position of the test pulse along the sweep line and the depth of the reflector (flaw) in the test piece. The ASTM distance/amplitude blocks provide a means of sweep range calibration with straight beam technique. It is recalled that the only variable of the distance/amplitude calibration blocks is the test metal distance. As illustrated in Figure 32-2-17, the sweep range calibration using Delay and Range controls correlates the location of the pulse on the sweep line with the depth of the reflector in the test piece.

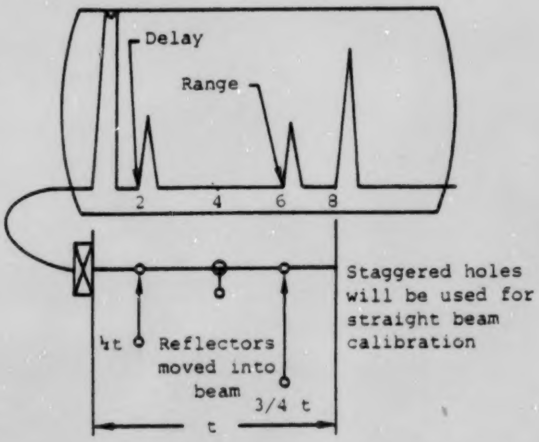

Delay
Range
2
4
6
8
Staggered holes will be used for straight beam calibration
¼t
Reflectors moved into beam
3/4 t
t

Figure 32-2-17 Beam Calibration

The electronic circuits of UT units provide a "time window" for the receive mode which is synchronized with the transmit mode. Only echos received during the "time window" are displayed on the CRT. The Delay control adjusts the real-time relationship between the time window and the instant of pulse transmission. With the CRT sweep starting coincident with pulse transmission, adjustment of Delay varies the location along the sweep of a pulse from a given reflector. With the search unit positioned to MAXIMIZE response from a reflector at a test metal distance corresponding to ¼ thickness of material to be examined, Delay is adjusted to position the pulse on the sweep, for example at line 2. The Range control adjusts the duration of the "time window". Thus, Range adjusts the relative sweep position between pulses from reflectors at different depths. With the search unit positioned to maximize reponse from a reflector at a test metal distance corresponding to 3/4 thickness of material to be examined, Range is adjusted to position the pulse on the sweep, for example, at line 6. Accordingly, Delay establishes sweep position of the ¼t reflector at line 2 and Range establishes sweep position of the 3/4t reflector at line 6 in this discussion. With this relationship, sweep line 4 represents ½t and sweep line 8 represents t where t equals material thickness. It is noted that Delay and Range controls interact somewhat, and sweep range calibration requires repeating the adjustments at ¼t and 3/4t two or more times.

Distance amplitude calibration correlates the displayed pulse height with the depth of a constant size reflector. Dependent on such factors as beam divergence and wave attenuation, a given size reflector gives different heights of displayed pulses for different depths of the reflector. The ASME block using side drilled holes or the ASTM distance/amplitude blocks provide means of distance amplitude calibration. With the Sensitivity control unchanged, the pulse heights from a given size reflector is plotted against depth of the reflector (test metal distance). A curve similar to that in Figure 32-2-18 is obtained. A distance amplitude curve (DAC) for test applications is drawn on the CRT screen by connecting the peaks of the pulses from ¼t, ½t, and 3/4t reflectors of the calibrated blocks.

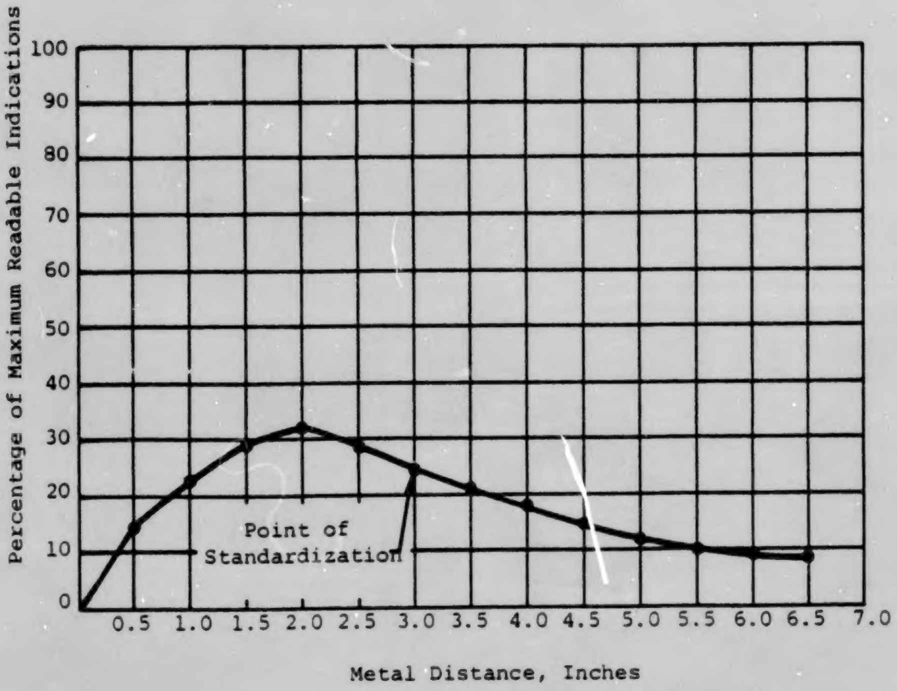


Figure 32-2-18 Typical Distance/Amplitude Response Curve

Flaw Detection

The minimum detectable flaw size depends on the wavelength (λ) being used for the test as given by:

$$r \geq \lambda \qquad \text{Equation 32-2-2}$$

Where:

r = the flaw radius, or one-half its diameter

Equation 32-2-2 indicates that for a flaw to be detectable, it must be at least one-half of a wavelength in diameter. This allows the selection of an appropriate frequency by using:

$$f = \frac{c}{(\frac{\lambda}{2})}$$ Equation 32-2-3

Where:

f = test frequency
c = acoustical velocity
λ = wave length

Given a metal with a velocity of sound equal to approximately 6000 $\frac{m}{sec}$, the following table lists some corresponding flaw diameters and minimum frequencies:

Table 32-2-1

Minimum Frequency Versus Flaw Size

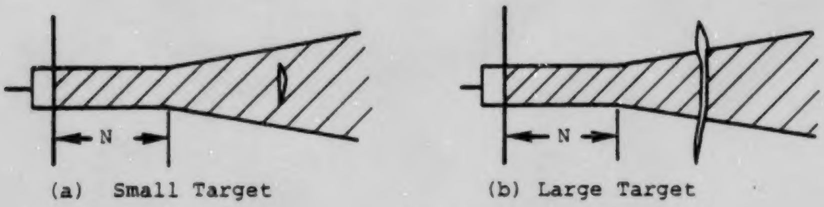
diameter (mm)	λ (mm)	f (MHz)
0.5	1	6
1	2	2
2	4	1.5
4	8	0.75
6	12	0.5

It should be recalled that the orientation of a discontinuity affects its reflective ability and its echo strength. However, the question of detectability is essentially one of the interaction between a wave and a reflector.

FLAW POSITION, SIZE, AND SHAPE FOR STRAIGHT BEAM TESTING

In straight beam testing, the determination of flaw position, size, and shape is quite simple and to some extent has already been discussed in this module. For a straight beam, the depth of a flaw is read directly off the A-scan display. For position in the plane parallel to the surface, as a C-scan gives, the probe merely has to be maneuvered until the point or region of maximum indication is located. This is simple for a small target but somewhat harder for a large target.

The definition of a small target or flaw is that it is smaller than the ultrasonic beam at its depth. A large target is one that is larger than the ultrasonic beam at its depth. This is illustrated in Figure 32-2-19.



(a) Small Target (b) Large Target

Figure 32-2-19 Target Size N stands for near field, the remainder is far field.

Flaw shape and size can usually be determined for a large flaw by tracing the outline of the flaw. One technique for outlining a large flaw is illustrated in Figure 32-2-20. For laminations, multiple back wall echoes from an unflawed section are presented on the CRT screen as in Figure 32-2-20(a). The search unit is then maneuvered to

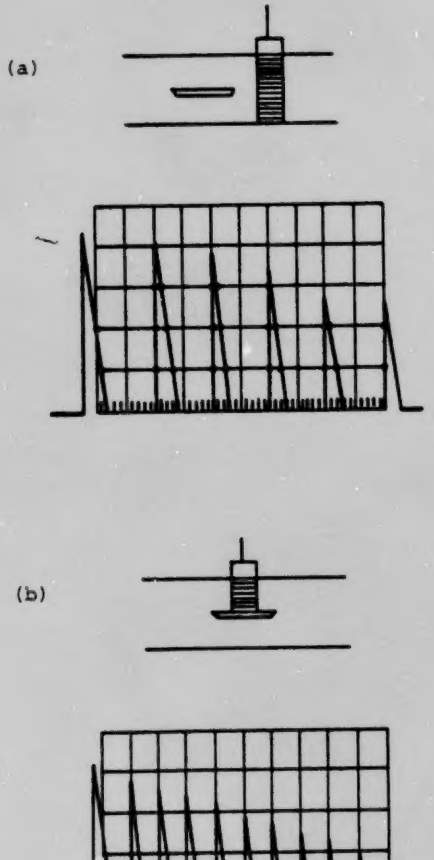


Figure 32-2-20 Flaw Indications

obtain a multiple echo pattern from the flaw with complete loss of back wall reflections as shown in Figure 32-2-20 (b). The search unit is then maneuvered to trace the flaw by noted when both sets of multiple echoes appear on the CRT, as illustrated in Figure 32-2-20(c).

For small flaws, it is very difficult to say much about their shape, and a technician is rarely required to do so. What is important for small flaws, or discontinuities, is to determine their size. This can be done by using a distance-gain-size (DGS) curve or a DGS overlay for the CRT screen. This curve is essentially a series of DAC curves at different values of flaw sizes. The DGS curve most commonly comes into use as an overlay specific to the instrument being used. Rather than requiring actual measurement of flaw size, codes and standards may merely require comparison of pulse height to the DAC curve established by calibration on a test block. In such cases, any indication larger than the DAC curve is reported as a flaw.

Flaw Position and Size for Angle Beam Testing

The angle beam techniques introduce a new concern in that the search unit is not directly over the flaw as is the case with straight beam. It is recalled that sweep calibration for A-scans establishes definite sweep positions for the ¼, ½, and 3/4 thickness. Thus, sweep location of the flaw indicates the depth of the flaw. Position of the flaw from the angle beam search unit is determined by a ruler which is scribed in conjunction with sweep calibration. As indicated in Figure 32-2-21, the ruler is placed against the search unit and scribed at the location of the scribe lines on the calibration block which coincide with the location of the side drilled holes and otherside notch (see Figure 32-2-15). Such a ruler can be scribed from the calibration using the IIW standard blocks. Material flaw location is formed by placing the calibrated ruler against the search unit located to maximize the response and locating the point on the ruler which corresponds to the echo-pulse sweep position.

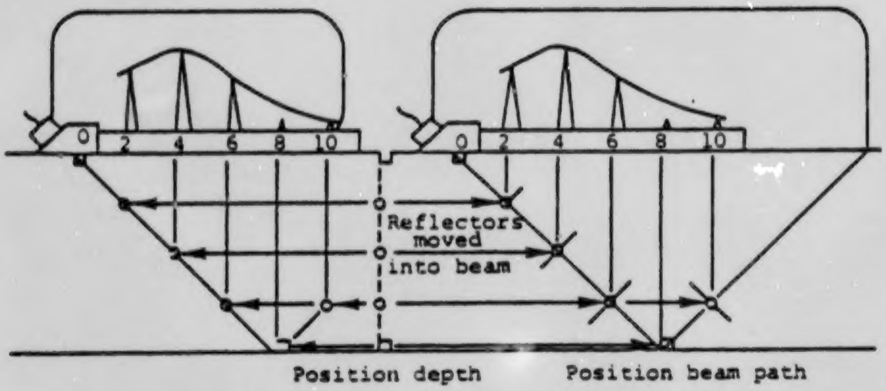

0
2
4
6
8
10
Reflectors moved into beam
Position depth
Position beam path

Figure 32-2-21 Angle Beam Position Calibration

Flaw size measurements by angle beam are made typically by tracing the search unit positions which yield an echo pulse amplitude corresponding to 50% DAC. The 50% DAC is established during calibration by connecting the pulse peaks from the side drilled holes where amplitude of the peaks is 50% of the established DAC. Figure 32-2-22 illustrates the 50% DAC established during calibration. It is noted that beam spread is also determined by the 50% DAC calibration.

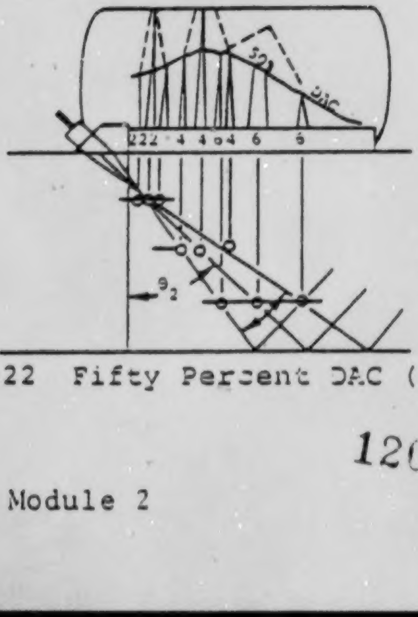

50% DAC
222 4 4 64 6 6
θ2

Figure 32-2-22 Fifty Percent DAC (Beam Spread)

Special Test Problems

Material properties which determine the ability to ultrasonically test a metallic sample are acoustic velocity and grain size. These properties are strongly affected by the material's heat treatment and less strongly by the material's alloy composition. In point of fact, the variations in acoustic velocity of different steels are quite small, on the order of or less than 5%. For survey tests or "rough-and dirty" quick scans, variations of that size can be neglected for tests using longitudinal waves. For angle beam tests, however, a 5% error in sample acoustic velocity could imply an approximate error of 3° at a 45° test angle in the sample material. Therefore, the calibration blocks should be of exactly the same material as the test sample. To eliminate as much of the grain-size problem as possible, the calibration block should have received exactly the same heat treatment as the test sample.

Special grain size problems occur in various high alloy steels. If coarse grains form, as is common in high alloy steels, large variations in scattering, and hence attenuation may occur within the test material. On the other hand, some stainless steel alloys have extremely low attenuation factors, which can cause spurious echoes. These spurious echoes, are actually late multiple echoes. They can be avoided by reducing the pulse repetition rate of the equipment.

A most critical problem for nuclear ultrasonic testing is the attenuation problem in austenitic weld material. This attenuation decreases the reliability of an ultrasonic examination of a weld, and may even preclude a complete examination of the weld. Attenuation in austenitic welds is primarily due to large columnar grains, called dendrites, formed by the slow, directional cooling during the weld process. Because these dendrites exhibit large changes in acoustic impedance at their boundaries, a substantial portion of a test beam can be reflected at these grain boundaries. This means that small defects are less likely to be located in an austenitic weld than in a ferritic weld.

The most important means of controlling the problem of attenuation is to carefully control the welding process. If the grains are oriented correctly, attentuation can be minimized. This, however, is of no use to an NDE technician once the weld is complete. The only thing to be done then is to alter the UT technique.

There are three techniques which show promise, but which have not yet been approved for nuclear use by ASME and NRC. These techniques include pitch-catch transducers, focusing probes, short pulses, and longitudinal waves as opposed to single, non-focusing probes, normal length pulses, and transverse waves. If equipment availability precludes these test techniques, test frequency selection is about the only method of reducing attenuation. Since resolution decreases with frequency, the best selection of test frequency is approximately 1 MH_z. While this frequency is not ideal for either attenuation or resolution, it represents a good compromise.

Other particular problems for nuclear QA/QC technicians concern uranium, zirconium, hafnium, and zircalloy tubes. Plates and rods of metallic uranium are normally tested by the immersed transmission method at 1 to 2 MH_z. Hafnium can also be immersion tested to 5 MH_z , while ingot form. Zirconium ingots are most frequently contact tested at 1 MH_z by the pitch-catch pulse echo technique.

Zircalloy tubes, used for fuel cladding, are immersion tested with pitch-catch transducers. They are generally guided past the transducers, which remain fixed, by a revolving feed mechanism. This method is used by vendors and utilities for manufacturing checks and acceptance tests.

Special Test Problems in Non-Metals

Very dense burnt porcelians used as insulators are ultrasonically tested during manufacture. Glass is not, in practice, tested using UT. Detectable faults include cracks, shrinkages, and inclusions. Care should be taken to account for differences in acoustic velocity between nominally similar porcelains depending on the supplier.

Plastics include a very wide range of material properties, from lucite to teflon to polyethelene. This range of materials demonstrates great variability in absorption of ultrasound. Frequencies of interest in testing plastics are in the low megahertz range. Wear on metal faced probes used to test plastics may be disregarded. Pitch-catch transducers are preferable, especially in thin samples to eliminate dead zones. The immersion technique offers a good acoustic match between the plastic and water, better than with metal, which means less loss due to interface reflections. Transverse waves do not propagate well in plastic, necessitating the use of longitudinal waves.

Concrete may only be ultrasonically tested at frequencies of 100 KH_z or less due to the inheterogentiy of the material. The largest problem with this frequency range is the lack of resolution due to poor beam directionality. Barium titanate is the most commonly used transducer material, although various types of magnetostrictive receivers are sometimes used. An evaluation of the acceptability of concrete can usually be made by measuring the longitudinal velocity of sound in the concrete.

Many other special test situations occur in UT work but are of little interest to the nuclear QA/QC technician, for example, these include the measurments of fat and meat thickness on pigs.

EXERCISES

Determining Position, Shape, and Level

In addition to the testing and measuring of materials, ultrasound may be used as a pure sounding method. It can be used to locate almost any change in density, such as the presence of air bubbles or foreign matter in a pipe or other container, to determine water level in a tank, or to locate accurately pieces welded to the back side of a plate.

1. Sketch a 45° angle beam search pattern for the test specimen illustrated in Figure 32-2-23.

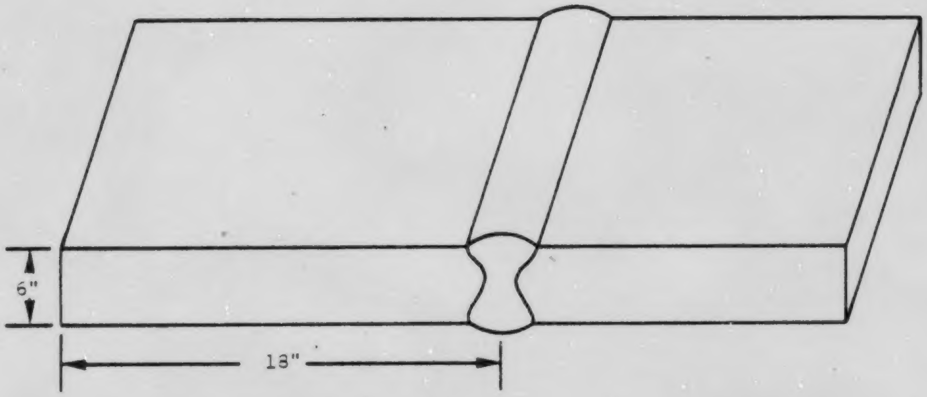


Figure 32-2-23 Welded Specimen

2. Prepare for the Procedures of this module by studying the ultrasonic test equipment manufacturer's technical manual and visually observing the equipment, probes, and cables.

MATERIALS

The following materials are required to support this module:

1. Portable ultrasonic pulse-echo test unit, with 2.25 MH$_z$ single and dual transducers and cables.
2. Couplants (30 wt. oil)
3. Grease pencils
4. ASTM distance-amplitude calibration blocks
5. ASTM area-amplitude calibration blocks
6. IIW standard reference block
7. Assorted material specimens

PROCEDURES

1. Construct an area-amplitude curve for a contact, pulse echo test system using the longitudinal wave technique:
   a. Energize the test unit and allow warm up time in accordance with the manufacturer's technical manual.
   b. Select a number 5 area-amplitude reference block.
   c. Select 2.25 MH$_z$ test frequency.
   d. Place couplant and the search unit on the top surface of the block, slightly off center.
   e. Manipulate the probe until a maximum bottom-hole response is obtained. (NOTE: If not preset, the Position controls may have to be adjusted to bring the echo-pulse on screen.)
   f. Adjust the Sensitivity until the CRT pulse height of the bottom-hole indication is 30% to 35% of the maximum obtainable on the CRT screen.

   g. Replace the number 5 block with the other area-amplitude blocks available.
   h. Record each indication's height or amplitude using the same sensitivity setting established with the number 5 block.
   i. Plot the amplitudes as a percentage of maximum pulse height, versus the square of the block number, on Data Table 32-2-1.
   j. Draw a straight line through origin and the data point for the number 5 block's amplitude. This is the line of ideal linearity. Significant deviations from this line are used to correct readings on actual flaws at that distance.

2. Construct a distance-amplitude curve for contact, pulse echo system using longitudinal wave technique:
   a. Energize the equipment and allow warm up time in accordance with manufacturer's technical manual.
   b. Select a number of 5-0300 distance-amplitude reference block.
   c. Place the couplant and the probe on the top surface of the block slight off center.
   d. Select a 2.25 MH_z test frequency.
   e. Manipulate the probe until a maximum bottom-hole response is obtained.
   f. Adjust the gain until the CRT pulse height of the bottom hole indication is approximately 25% of the maximum obtainable on the CRT screen.
   g. Replace the No. 5-0300 block with the other distance amplitude blocks available.
   h. Record each indication's height or amplitude using the gain setting established for the No. 5-0300 block.

i. Plot on Data Table 32-2-2 the amplitudes as a percentage of maximum pulse height versus the metal distance for each block. The resulting curve should be similar to Figure 32-2-18, with pulse height increasing in distance in the near field, and decreasing with distance in the far field.

3. Determine beam angle and beam spread using an IIW Standard Reference Block:
   a. Energize the test system and allow warmup time in accordance with manufacturer's technical manual.
   b. Select 2.25 MH_z test frequency.
   c. Select or assemble dual unit search probe and 45% weld.
   d. Place couplant and search unit on surface A of the reference block at the focal point scribe line and such that the angle beam is directed toward the four inch radius.
   e. Position the search unit to maximize the back wall reflection from the radius and scribe the search unit at the point corresponding with the focal point of the reference block. This marks the index point of the search unit.
   f. Place couplant and search unit on surface B of the reference block such that the angle beam is directed toward the two inch diameter circular cutout.
   g. Position search unit to maximize response from the two inch circle and read beam angle at the coincidence of the index point of the search unit and the inscribed angle scale adjacent surface B.
   h. Position search unit either side of beam angle and note the angle at which the response from the two inch circle disappears. Calculate beam spread by subtracting these two angles.

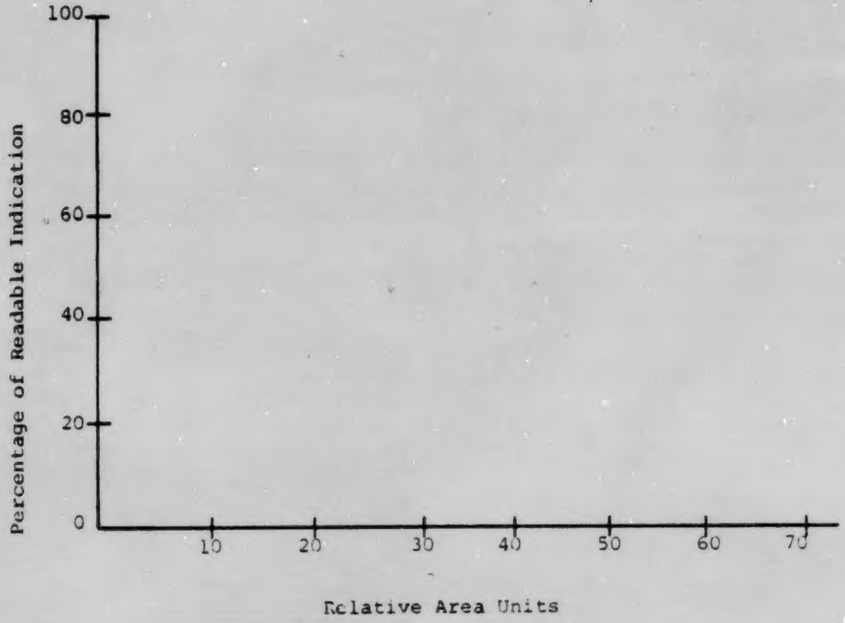
4. Ultrasonically test by longitudinal wave technique a material specimen provided by the instructor:
   a. Energize the test equipment and allow warmup time in accordance with the manufacturer's technical manual.
   b. Select 2.25 MH_z test frequency.
   c. Select three ASTM distance-amplitude calibration blocks having test metal distances of ¼t, ½t, and 3/4t where t equals thickness of the material to be examined.
   d. Perform sweep calibration by testing each block and adjusting Delay and Range such that the ¼t and 3/4t responses correspond to sweep lines 2 and 6 respectively. (See module subject matter for help.)
   e. Test the calibration block which gave the highest pulse while performing sweep calibration and with the response maximized, adjust Sensitivity to obtain a pulse height of 80% of full CRT screen height. Mark the peak of the response on the screen with a grease pencil.
   f. Test the two remaining reference blocks at the same sensitivity setting and mark the peaks on the screen with a grease pencil.
   g. Connect the three marks on the screen to form the DAC.
   h. With the attenutation switch, add 6 db gain (double the gain).
   i. Apply couplant to the test material and scan the material using parallel scanning paths with at least 10% overlap.
   j. Whenever indications are noted, maximize the response, return attenuator to original setting, record pulse

amplitude as either above or below DAC, and record flaw depth by noting position in sweep. Mark the location of the flaw on the test specimen by outlining the search unit.

DATA TABLE

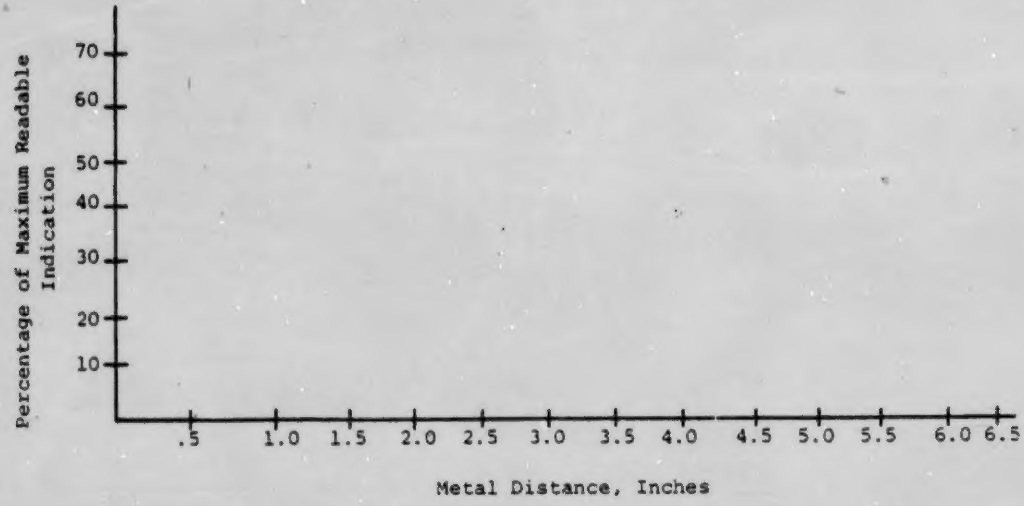
Data Table 32-2-1

Area-Amplitude Calibration



Data Table 32-2-2

Distance Amplitude Curve



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TEST

A. Multiple Choice:

Circle the most correct answer following each question which follows:

1. The search unit used in immersion testing is frequently varied in position and orientation to change the angle of refraction in the test piece. This is referred to as:
   (a) angulation (c) attenuation
   (b) dispersion (d) calibration

2. The preferred ultrasonic testing method for detecting flaws oriented parallel to the surfaces of a plate is:
   (a) angle-beam contact method with surface waves.
   (b) straight-beam contact method with longitudinal waves.
   (c) immersion test using surface waves.
   (d) angle beam contact method with transverse waves.

3. When inspecting aluminum by the immersion method using water for a couplant, the following information is known: velocity of sound in water (1.49 km/sec) and aluminum (6.30 km/sec), and the angle of incidence equal 5°. The angle of refraction for longitudinal waves is approximately:
   (a) 16° (c) 22°
   (b) 18° (d) 26°

4. In general, ________________ waves will travel around gradual curves with little or no reflection from the curves.

(a) transverse (c) torsional
(b) surface (d) longitudinal

5. When using two separate probes, one functioning as a transmitter, the other as a receiver, the most efficient combination would be:

(a) a quartz transmitter and barium titanate receiver
(b) a barium titanate transmitter and a lithium sulfate receiver
(c) a lithium sulfate transmitter and a barium titanate receiver
(d) a barium titanate transmitter and quartz receiver

6. In immersion testing, the water distance between the search unit and the test piece should be:

(a) as small as possible
(b) the same as the thickness of the test piece
(c) the same as the water distance used during calibration
(d) as great as possible.

7. Defects near the entry surface cannot always be detected due to:

(a) far field effect (c) refraction
(b) attenuation (d) test system recovery time

8. Angle-beam testing is most likely to miss:
   (a) cracks perpendicular to the sound wave
   (b) cracks parallel to the front surface
   (c) randomly oriented inclusions
   (d) a series of small discontinuities

9. Under most circumstances, which of the following frequencies would result in the best resolving power?
   (a) 0.5 MH_z
   (b) 1.0 MH_z
   (c) 3.0 MH_z
   (d) 5.0 MH_z

10. Metal blocks containing one or more drilled holes to simulate discontinuities are called:
   (a) scrubbers
   (b) reference blocks
   (c) crystal collimators
   (d) angulators

11. In general, transverse or shear waves are more sensitive to small discontinuities than longitudinal waves for a given frequency and in a given material because:
   (a) The wavelength of transverse waves is shorter than the wavelength of longitudinal waves.
   (b) Transverse waves are less easily dispersed than longitudinal waves.
   (c) Transverse waves travel faster than longitudinal waves.
   (d) The wavelength of transverse waves is longer than the wavelength of longitudinal waves.

12. Which ultrasonic test frequency would most reasonably provide the best penetration of a 12-inch thick specimen of coarse grained steel?

(a) 5 MH_z (c) 10 MH_z
(b) 1 MH_z (d) 2.25 MH_z

13. Generally, the best test method for detecting discontinuities oriented along the fusion zone in a weld is:

(a) an angle beam contact method for surface waves
(b) a contact method using straight longitudinal waves
(c) an immersion test using surface waves
(d) an angle beam method using shear waves

14. Which of the following is not an advantage of contact probes adapted with lucite shoes?

(a) little crystal wear
(b) adaptation to curved surfaces
(c) increased sensitivity
(d) varied entry angles for test beam

15. The angle of reflection of an ultrasonic beam at an aluminum-water interface is ____________ the angle of incidence.

(a) ½ (c) equal to
(b) 4 times (d) .256 times

16. A weld inspection ruler or calculator is used in _______________ testing.
   (a) straight beam pulse echo
   (b) angle beam pulse echo
   (c) straight beam resonance
   (d) straight beam transmission

17. The DAC curve provides a means of:
   (a) determining acceptance of flow size
   (b) calibrating for linearity
   (c) locating the depth of flows
   (d) scribing the index point

B. Short Answer, Problem and Essay Questions:

Answer the following questions as indicated:

1. State the physical property of lucite that makes it a good choice of material in an angle-beam wedge adaptor in a probe and briefly explain why.

2. Differentiate between squirter and bubbler techniques.

3. What is the identification code number of an ASTM standard reference block with a height of 4 3/4 in. and a hole diameter of 7/64 in.

4. What minimum frequency must one use to detect a 3 mm diameter flaw in metal with $C_1 = 6000 \frac{m}{sec}$.?

5. In order to measure, the thickness of a sample, the acoustic _____________ of the sample must be known.

6. A large columnar grain, frequently found in austenitic welds, is called a _______________.

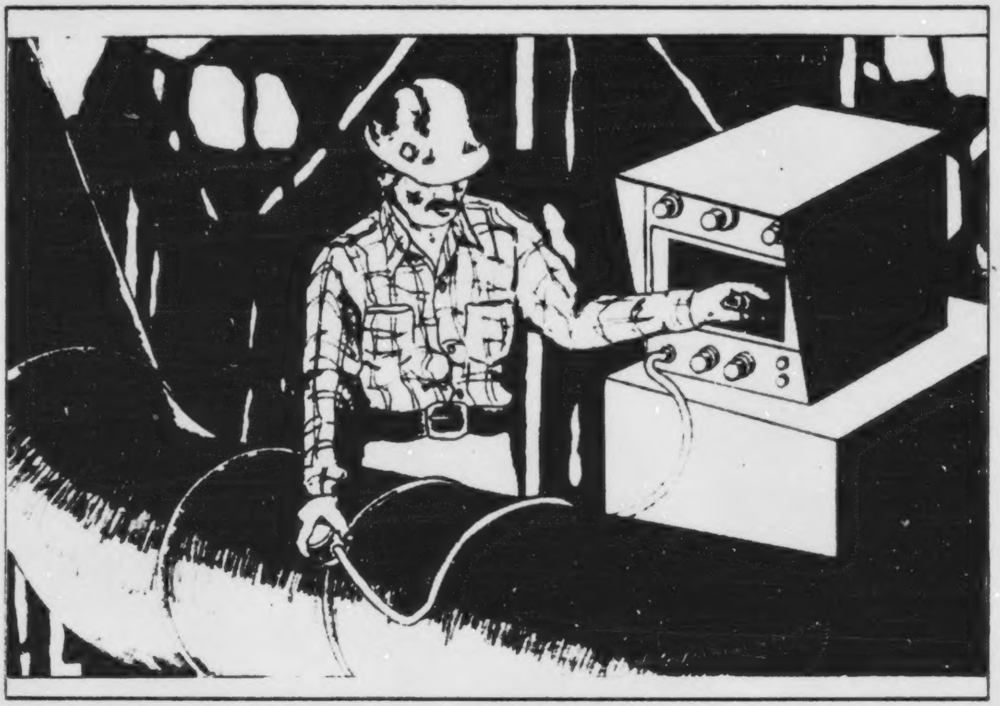
7. A test frequency of ______________ is best for examination of austenitic weld material.

8. ________________ waves should be used in examining plastics.

NUCLEAR TECHNOLOGY

MODULE 32 - 3

FUNDAMENTALS OF MAGNETIC PARTICLE TESTING



COURSE 32: NONDESTRUCTIVE EXAMINATION (NDE)

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

MODULE 32-1	Fundamentals of Ultrasonic Testing
MODULE 32-2	Operation of Ultrasonic Test Equipment
MODULE 32-3	Fundamentals of Magnetic Particle Testing
MODULE 32-4	Operation of Magnetic Particle Test Equipment
MODULE 32-5	Fundamentals of Eddy Current Testing
MODULE 32-6	Operation of Eddy Current Test Equipment

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INTRODUCTION

One of the most widely used methods of nondestructively examining and evaluating materials, fabricated components and weldments, is magnetic particle testing. The QA/QC technician may encounter or be responsible for performing, evaluating, or witnessing magnetic particle tests in a number of various settings and activities, such as mechanical equipment manufacture and installation, piping fabrication and installation, equipment modification and repair, and inservice inspection of welds in power plants.

Simply stated, the method consists of (1) inducing a magnetic field in the article to be examined, and (2) applying magnetic particles to the surface of the article. Material defects or discontinuities affect the induced magnetic field, and corresponding patterns are formed by the magnetic particles on the surface indicative of the discontinuities which exist.

This module explains the principles of magnets and magnetic fields and how they are applied in magnetic particle testing, describes the theory and methods of magnetizing test specimens, describes the test equipment used, discusses the principles and reasons for demagnetization, and describes the applicability, advantages and disadvantages of specific test methods.

The operation of test equipment, descriptions of the types of discontinuities detected, and the recognition and interpretation of test indications will be covered in Module 32-4.

MODULE PREREQUISITES

The student shall have completed all previous modules of Course 32.

OBJECTIVES

Upon completion of this module, the student/trainee can;

1. Answer correctly applicable questions on topics covered in this module as selected from the Level II SNT-TC-1A certification written test. Note: the topics and information needed to prepare the student/trainee for the SNT-TC-1A test which are not covered in this module, are covered in Module 32-4.
2. Answer correctly with a score of 80% or better a set of written exercises covering the following topics:
   (a) principles of magnets and magnetic fields.
   (b) magnetization of test specimens
   (c) principles and methods of demagnetization
   (d) application of inspection media
   (e) permeability and retentivity of materials
   (f) characteristics of discontinuities
   (g) characteristics of test equipment: applicability, advantages, & disadvantages with respect to typical test specimens.
3. Examine actual or illustrated test specimens and specify appropriate methods of magnetization, inspection media application, and methods of demagnetization.

4. Examine illustrations of test equipment, such as power supplies, prods, coils, head stocks, yokes, etc., and identify key parts and controls, and explain the operation and/or use of each.
5. Describe the basic methods of magnetization and explain the advantages and disadvantages of each.
6. Describe the applicability, advantages and disadvantages of using the following devices for magnetizing each item given on a list of typical test specimens: prods, coils, yokes, permanent magnets, head stock contacts, and head stock central conductors.

SUBJECT MATTER

Principles of Magnets and Magnetic Field

A magnet is a body which has the property of attracting iron and producing a magnetic force field external to itself. This phenomenon occurs in an object when part or all of its molecules have their North and South poles oriented. When the molecules are oriented or aligned in this manner, the object, or magnet, has two distinct and opposite poles which are attracted by the earth's poles. Magnets have the property that "like poles repel" and "opposite poles attract". This ability to attract or repel is illustrated in Figure 32-3-1:

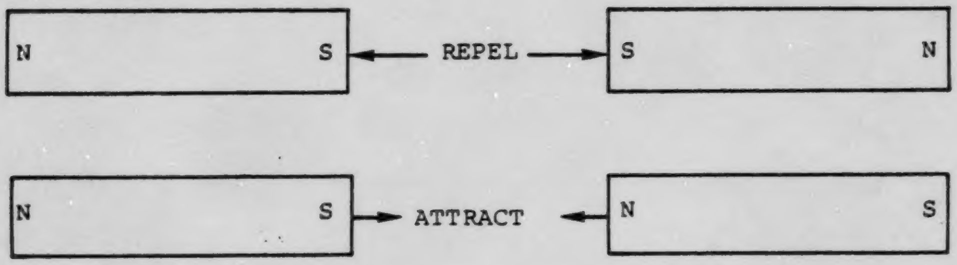


Figure 32-3-1 Magnetic Attraction/Repulsion

Since there is generally a uniform alignment of the molecules in a magnet, when a magnet is divided or broken, the resulting parts will be individual magnets with distinct North and South poles, as illustrated in Figure 32-3-2:

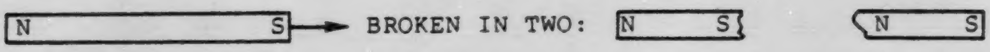


Figure 32-3-2 Division of a Magnet

The force field surrounding a magnet is not uniform, but is concentrated at the poles. If a sheet of paper is placed on a bar magnet, and iron filings or particles are sprinkled over the paper, the particles will be attracted and aligned by the magnetic lines of force as illustrated in Figure 32-3-3. The figure shows that the lines don't cross, and are densely arranged at the poles.

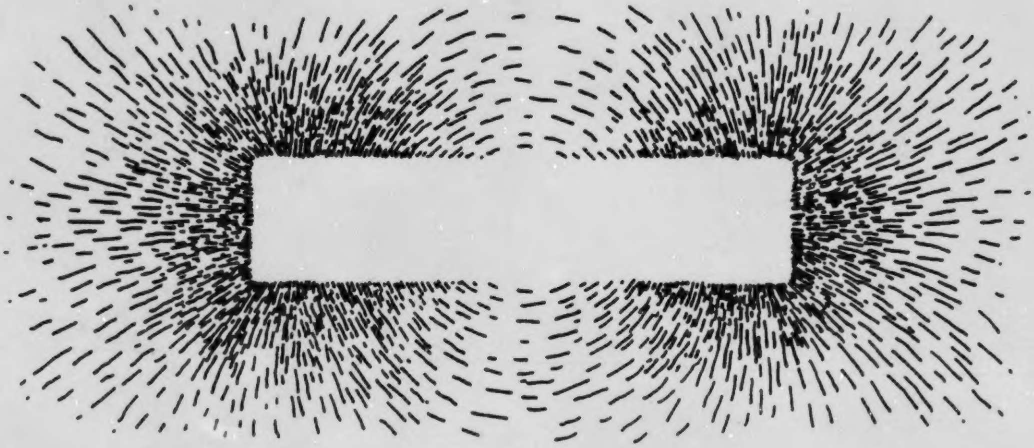


Figure 32-3-3 Magnetic Field Surrounding Bar Magnet

If the bar magnet is broken in half (thereby creating two magnets), and the paper and filings demonstration is repeated, the magnetic lines of force will be displayed as shown in Figure 32-3-4, with an accumulation of filings at the junction of the two magnetic parts.

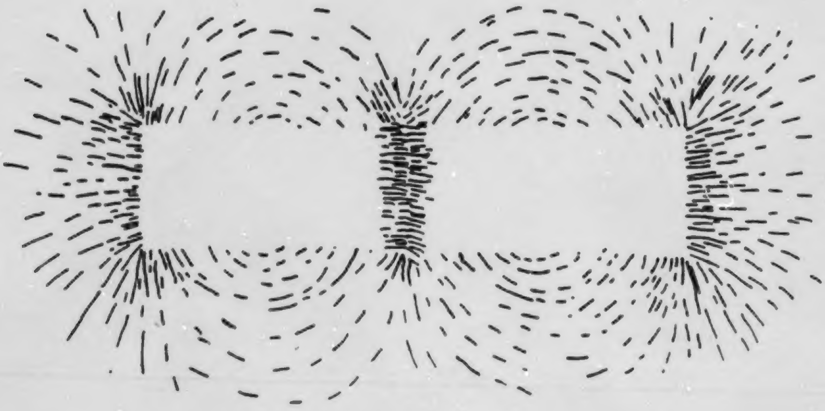


Figure 32-3-4 Magnetic Field Surrounding Broken Bar Magnet

The phenomenon illustrated in Figure 32-3-4 provides a basis for the magnetic particle inspection method: when a magnetic field or flux in an object is interrupted by a break or discontinuity in the material, a new flux pattern will be created, new poles will be formed, and iron particles will be attracted to that location.

When more than two poles exist simultaneously within a magnetized object, the poles are known as consequent poles.

Magnetic field characteristics are exhibited by both permanent and temporary magnets. Permanent magnets are those which retain their magnetism more or less permanently, and temporary magnets are those which retain their magnetism only as long as a magnetizing force is applied.

A magnetic field also exists around a conductor carrying an electric current. If the conductor has a uniform shape, the density of the flux is uniform at any point along the conductor, and decreases as the distance from the conductor increases. The circular magnetic field forms a closed loop pattern of lines of force around the conductor as shown in Figure 32-3-5. The direction of such an electrically induced magnetic field may be determined by using the "right hand rule", that is, if the right hand grasps the conductor with the thumb pointing in the direction of the current flow, the fingers will point in the direction of lines of force.

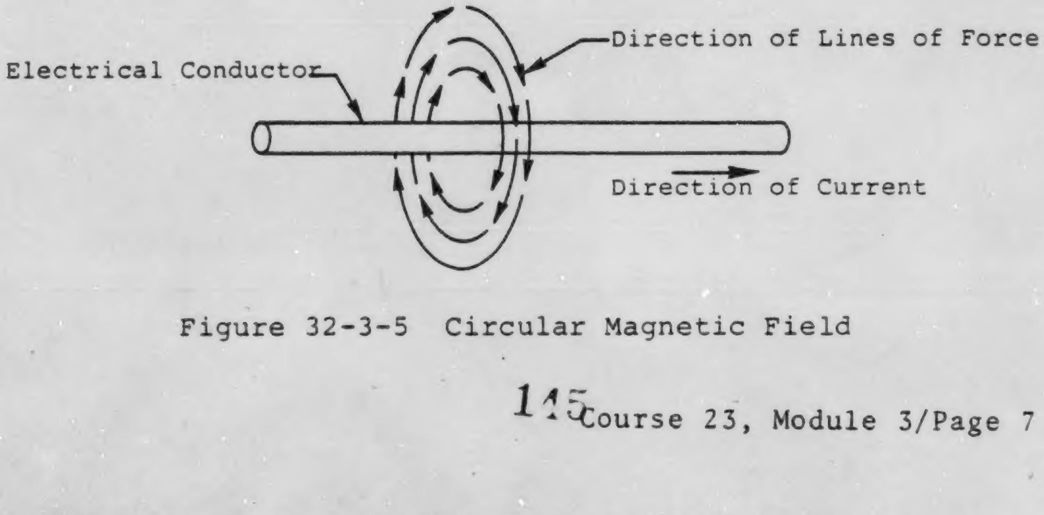


Figure 32-3-5 Circular Magnetic Field

If a current-carrying conductor is formed in a loop, as shown in Figure 32-3-6, the lines of force inside the loop will all point in the same direction, and a longitudinal magnetic field will be created.

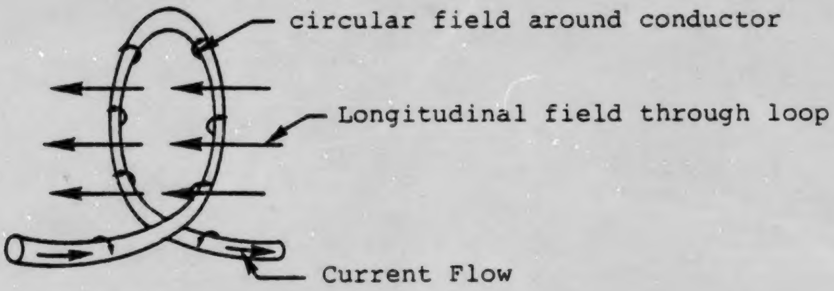

circular field around conductor
Longitudinal field through loop
Current Flow

Figure 32-3-6 Longitudinal Magnetic Field

As more loops are added to the coil, the magnetic field strength increases in proportion to the number of loops.

The magnetizing forces and resulting magnetic fields for any specific material can be represented graphically by plotting magnetizing force vs. flux density. The resulting diagram is known as the hysteresis curve for that material, as illustrated in Figure 32-3-7.

In this illustration, a piece of unmagnetized steel is exposed to a magnetizing force (H+) in incremental steps beginning at point 0, and the induced flux density (magnetic field) increases until it reaches point 1, beyond which any further increase in the magnetizing force does not increase the flux density. At this point, the material is said to be magnetically saturated. This plot, from 0 to 1, is defined as the virgin curve of the material.

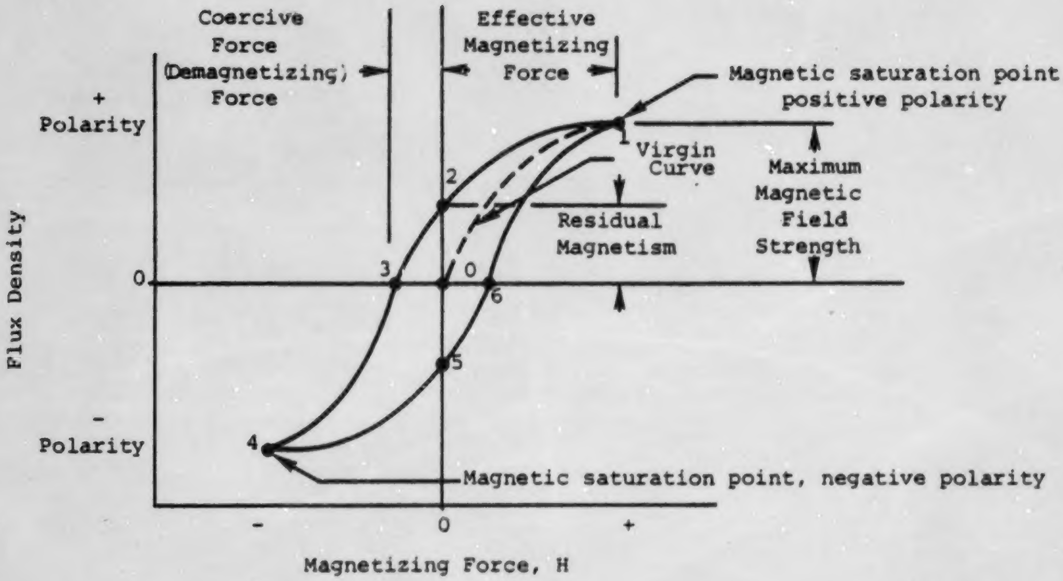


Figure 32-3-7 Hysteresis Curve

When the magnetizing force is reduced to zero, the flux density drops only to point 2. The remaining flux density, represented as 0-2, is residual magnetism. As a negative or reversed magnetizing force is applied, the flux density decreases to zero; this force, shown as 0-3, is the coercive force in the material. When the reversed magnetizing force is further increased, magnetic saturation is again achieved at point 4. As the magnetizing force diminishes to zero, the flux density decreases to point 5, again leaving a residual field. The magnetizing force is then applied in the positive direction to reduce the flux density back to zero, thereby completing the cycle. The area within the curve then represents the hysteresis characteristics, or the lag between the magnetizing force and the flux density throughout the magnetization/demagnetization cycle, for that particular material.

Different ferromagnetic materials have different magnetic properties, and consequently, have different hysteresis curve characteristics. If a characteristic curve exhibits a wide loop, the material will have high reluctance and be difficult to magnetize, but also will retain a high residual field. A curve with a narrow loop, however, represents material that magnetizes easily, but retains a weak residual field. Curves with these characteristics are illustrated in Figure 32-3-8.

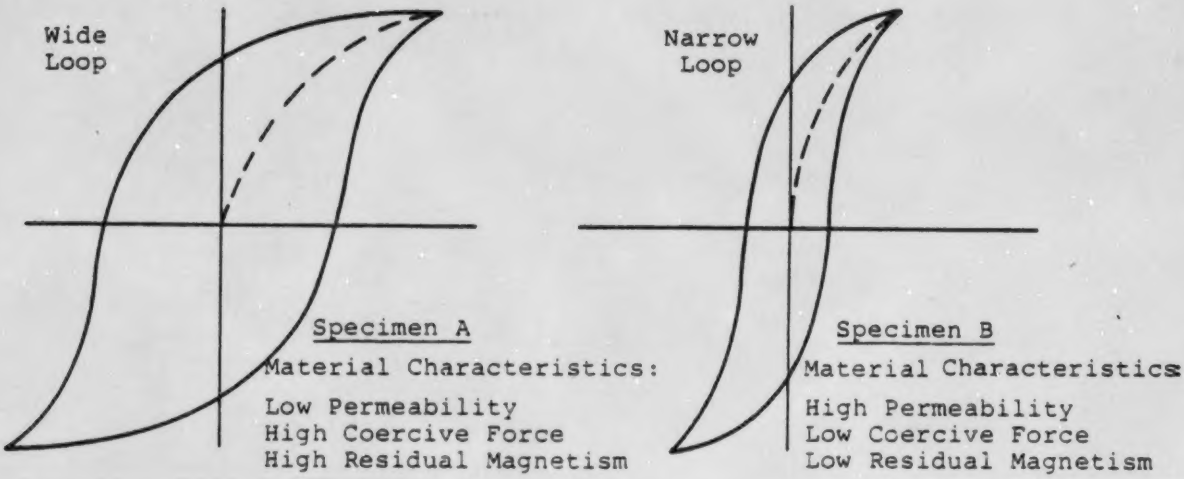
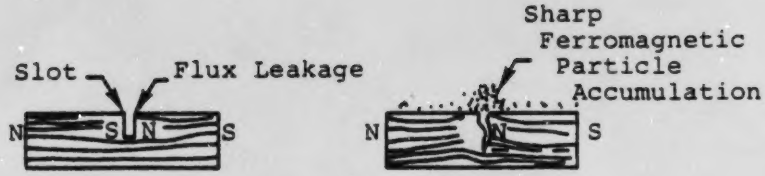
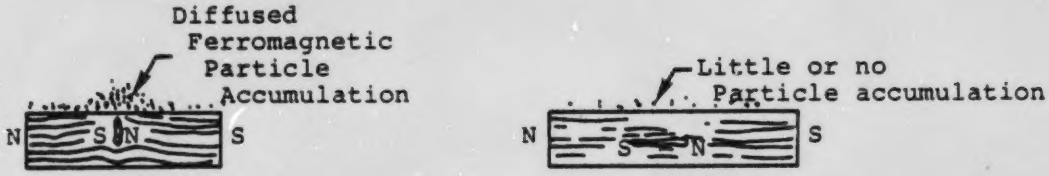

Wide Loop
Narrow Loop
Specimen A
Material Characteristics:
Low Permeability
High Coercive Force
High Residual Magnetism
Specimen B
Material Characteristics:
High Permeability
Low Coercive Force
Low Residual Magnetism

Figure 32-3-8 Comparison of Materials and their Respective Hysteresis Curves


Slot
Flux Leakage
N
S
N
S
Sharp Ferromagnetic Particle Accumulation
N
N
S

Surface Discontinuity

Surface Discontinuity


Diffused Ferromagnetic Particle Accumulation
N
S
N
S
Little or no Particle accumulation
N
S
N
S

Internal Discontinuity
(Normal to surface)

Internal Discontinuity
(Parallel to Surface)

Figure 32-3-9 Material Discontinuities and Orientation

Figure 32-3-9 illustrates that discontinuities that extend to the surface produce sharp, well defined indications, and shallow sub-surface discontinuities produce diffused indications consistent with the strength of the leakage field. When a discontinuity occurs at a greater depth, or its long axis is parallel to the surface, the leakage field is either very weak or is nonexistent on the surface, and the discontinuity cannot be detected with this technique.

Characteristics of Magnetizing Currents

The types of magnetizing currents best suited for, and normally used in magnetic particle testing, are alternating current and half-wave rectified current. Direct current is used to some extent with solenoids and yokes, and has excellent penetrating characteristics. However, it is not generally suitable for circular magnetization usage (where the current strength must be varied with the specimen size) since it cannot be stepped down in voltage with transformers.

Alternating Current

Alternating current has the characteristic that it reverses direction in a cyclical pattern, normally at a frequency of 60 hZ (cycles per second). Its wave form is shown in Figure 32-3-10.

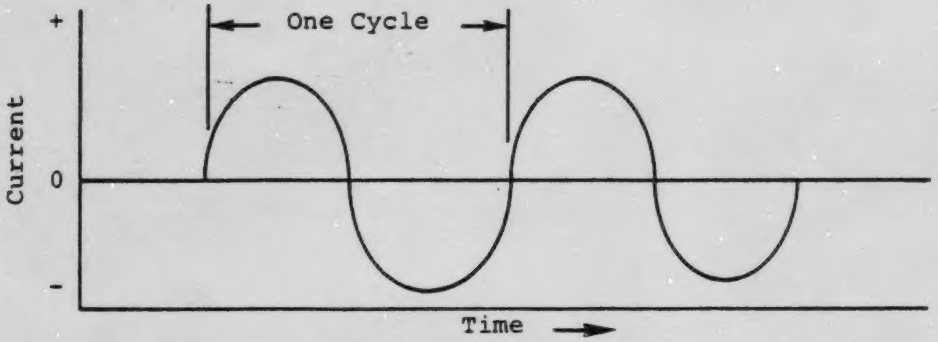


Figure 32-3-10 Wave Form, Single Phase Alternating Current

Beginning at a zero value, the current flow increases to a maximum positive value, decreases to zero, reverses direction, increases to a maximum negative value, and decreases again to zero, completing one cycle.

Alternating current (AC) has little penetrating ability, but creates a maximum magnetic flux at the surface of the specimen, a phenomenon known as the "skin effect". Consequently, AC is most useful for locating surface discontinuities.

AC can easily be stepped up or down with transformers and its characteristic of magnetic field reversal promotes the mobility of magnetic particles and their collection at leakage fields.

Half-wave Rectified Current

Alternating current is passed through a rectifier and converted to half-wave rectified, also called half-wave direct current (HWDC). The rectifier allows the current to flow in one direction only, as shown in Figure 32-3-11, preventing the current and subsequent magnetic field reversal.

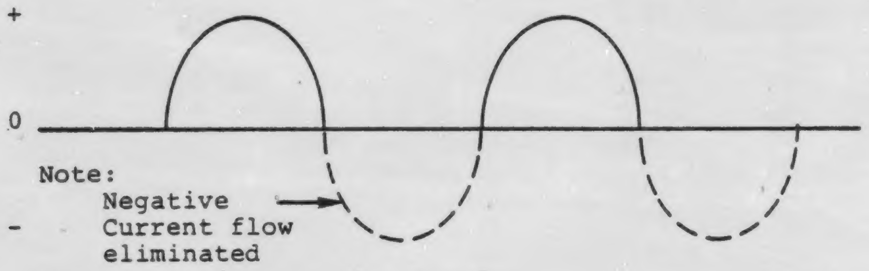


Figure 32-3-11 Wave Form, Half-Wave Rectified (Direct) Current

The resulting current is pulsating DC, with high penetrating ability and influence on magnetic particle mobility.

Since the hwdc is produced from AC, the voltage can be varied easily, and outputs for both types can be provided on the same power supply. Hwdc combines the pulsating advantage of AC for particle mobility with the penetrating advantage of DC, and is best suited for locating sub-surface discontinuities.

Methods of Magnetization

The following paragraphs describe the most commonly used methods of magnetizing specimens for magnetic particle inspection:

Coil or Solenoid Magnetization:

A specimen whose length is between 2 and 15 times its diameter and less than 18 inches in length may be magnetized with a longitudinal field by placing it in a current carrying coil as illustrated in Figure 32-3-12.

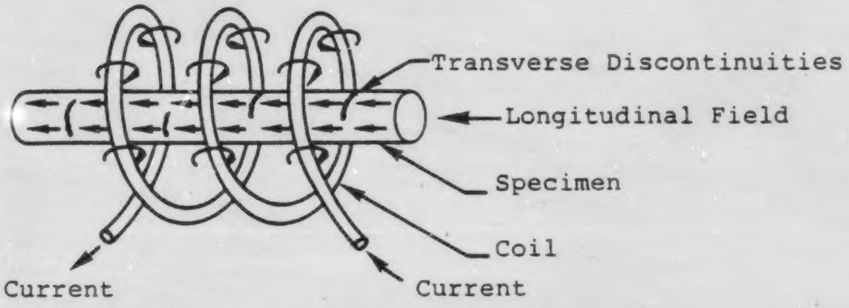


Figure 32-3-12 Coil (or Solenoid) Magnetization - Longitudinal Field

When using this technique, the specimen should be held against the inside wall of the coil and not positioned in the center of the coil.

The strength of the induced magnetic field is approximately proportional to the number of turns in the coil. For example, double the number of turns and the magnetic flux will be doubled. The length of the induced field is limited, however, and several "shots" may be required for a long specimen to adequately magnetize the entire part.

This method of magnetization is most effective in locating transverse discontinuities or defects which cross the induced longitudinal lines of flux, as illustrated in Figure 32-3-12.

Yoke Magnetization:

The yoke is a temporary soft iron horseshoe magnet which is magnetized by passing a current through its horizontally wound coil, as shown in Figure 32-3-13.

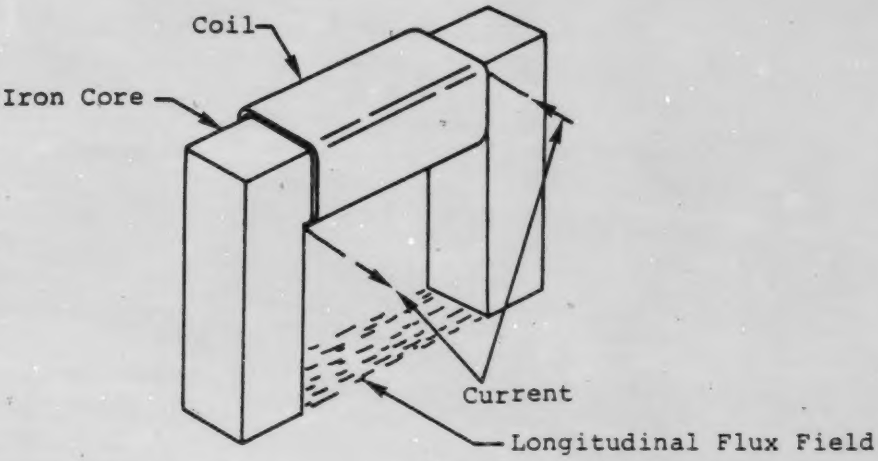


Figure 32-3-13 Yoke Magnetization

When the energized yoke is placed in contact with the surface of the specimen, a local longitudinal magnetic field is induced.

The force field produced by the yoke is constant and cannot be varied. The yoke is used most effectively on highly permeable (easily magnetized) materials, and locates discontinuities transverse to the induced field.

In using the yoke, the usual practice is to magnetize the specimen in one direction and inspect for defects, then magnetize the specimen a second time in the same area but in a direction rotated 90° from the first direction, and reinspect.

By using this technique, all discontinuities will be exposed more or less transversely to the magnetic flux lines, and will be detected.

Direct Induction Magnetization

A circular field may be induced directly in a specimen by passing a current through the article, as shown in Figure 32-3-14. Magnetization produced in this manner with stationary equipment is called a "head shot".

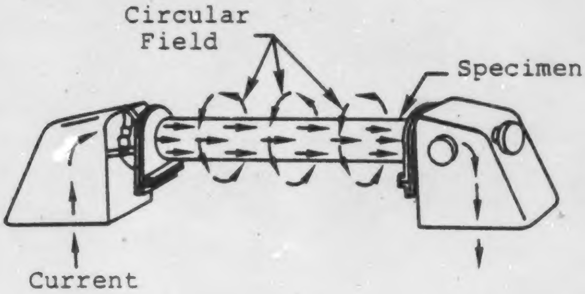


Figure 32-3-14 Direct Induction ("Head Shot") Magnetization

The magnetic field strengths resulting from the current flow vary from zero in the center of a solid specimen or the inside surface of a hollow specimen, to a maximum value at the surface.

Since this technique induces a circular magnetic field in the specimen, it is most useful for locating discontinuities oriented longitudinally in the specimen. To avoid the possibility of overlooking transversely oriented defects, such parts are usually inspected a second time with a longitudinal magnetic field.

Direct Induction Magnetization with Prods

A distorted circular field may be induced in a specimen by passing a current through the specimen by the use of portable (hand held) prods, as shown in Figure 32-3-15.

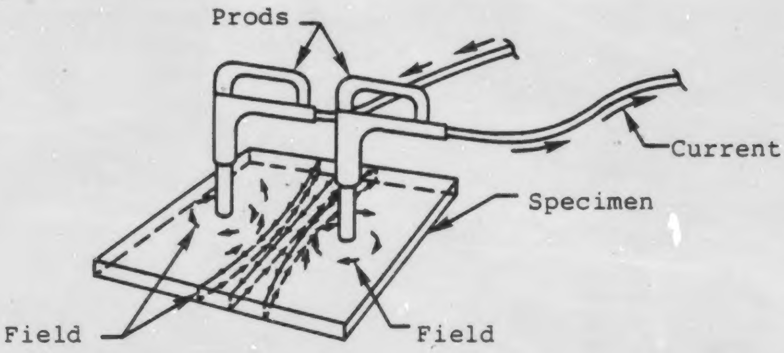


Figure 32-3-15 Direct Induction ("Prod") Magnetization

This technique is used widely for inspecting welds and many other applications where the size, shape or location of an article precludes the use of a head shot or a central conductor technique.

Permanent Magnet Yoke Magnetization

Adjustable permanent magnet yokes as shown in Figure 32-3-16, may be used to induce longitudinal magnetic fields in highly permeable materials. Permanent magnet yokes do not produce magnetic fields as strong as those produced by electromagnetic yokes, so their use must be limited to easily magnetized materials, and for investigating surface discontinuities only.

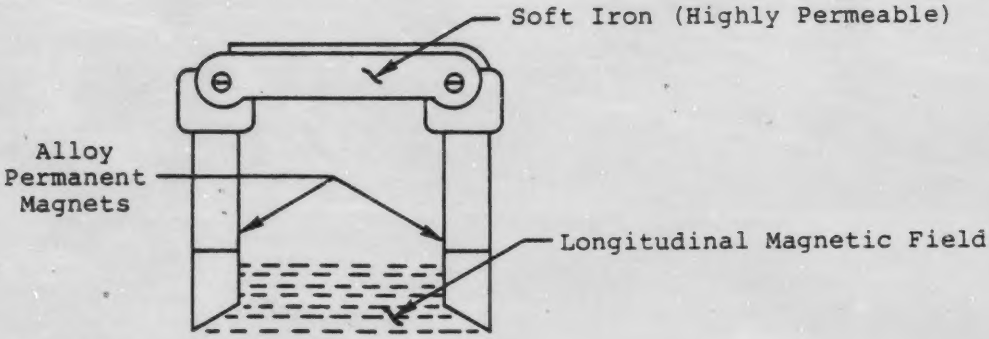

Soft Iron (Highly Permeable)
Alloy Permanent Magnets
Longitudinal Magnetic Field

Figure 32-3-16 Permanent Magnet Yoke Magnetization

Central Conductor Magnetization

A central conductor may be used to induce a circular field in a hollow specimen, as shown in Figure 32-3-17.

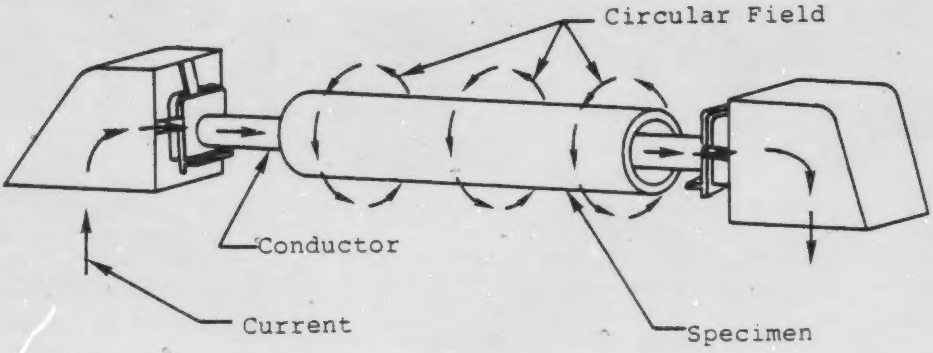

Circular Field
Conductor
Current
Specimen

Figure 32-3-17 Central Conductor Magnetization

Cable Magnetization

Large specimens may be magnetized effectively with the use of cables, as shown in Figure 32-3-18.

the test material. The flaws are flat-bottomed, drilled holes centered in the bottom of the blocks. All the blocks are two inches in diameter, and all the holes are three-quarters of an inch in depth. As illustrated in Figure 32-2-13(a) the hole diameter is fixed at one of three diameters and only the test metal distance varies among the blocks of a set. Thus, these blocks provide a constant size reflector at various, known test metal distances.

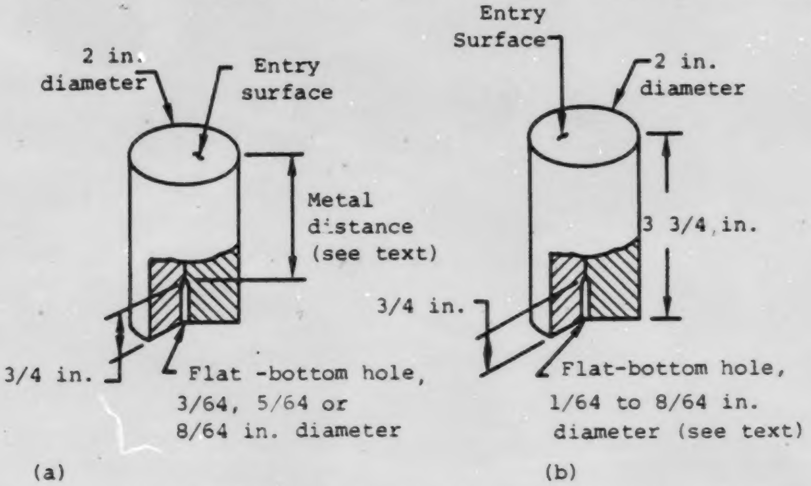

2 in. diameter
Entry surface
Metal distance (see text)
3/4 in.
Flat -bottom hole, 3/64, 5/64 or 8/64 in. diameter
(a)
Entry Surface
2 in. diameter
3 3/4 in.
3/4 in.
Flat-bottom hole, 1/64 to 8/64 in. diameter (see text)
(b)

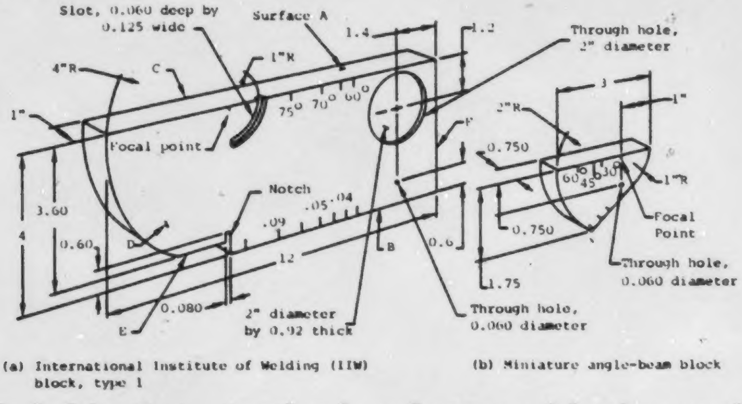
Figure 32-2-13 Standard reference blocks for use in straight-beam ultrasonic inspection: (a) distance-amplitude block and (b) area-amplitude block

The ASTM area/amplitude blocks provide a standard on reference depth of flaw, with the flaws being of various sizes or diameters. As illustrated in Figure 32-2-13(b), the flaws are, again, flat-bottomed holes drilled in the bottom of the blocks and centered. The blocks are, again, two inches in diameter with the bottom holes being three-quarters of an inch long. The metal distance is constant in this case, while the diameters of the hole of flaw differ. Thus, a set of area/amplitude blocks provides various, known flaw sizes at a fixed test metal distance.

Each of the area/amplitude and distance/amplitude blocks is identified by a five digit code number in the form of a single digit separated from four more digits by a dash. The first digit gives the diameter of the hole in sixty-fourths of an inch. The four remaining digits give the metal distance in hundredths of an inch. For example, a block marked 5-0600 has a flat bottomed hole diameter of five sixty-fourths (5/64) of an inch and a metal distance of 600 hundreths of an inch or six inches.

Because a flat-bottomed hole is a specular reflector, it will return an echo that is quite strong. Therefore, any equivalent strength echo from a real flaw will indicate a flaw cross-section larger than the flat-bottomed hole.

IIW -type blocks are used to calibrate equipment for either longitudinal or transverse (shear) examination and also to check the performance characteristics of an angle-beam search unit such as beam exit or index point and angle of refraction. IIW blocks come in both metric and English dimensions. Typical measurements are 12 in. x 4 in. x 1 in. Figure 32-2-14 shows a typical IIW standard block and an AWS miniature angle-beam block.


Slot, 0.060 deep by 0.125 wide
Surface A
1.4
1.2
Through hole, 2" diameter
4"R
C
1"R
75°
70°
60°
1"
Focal point
F
3.60
4
0.60
D
Notch
.09
.05
.04
12
B
0.6
0.080
E
2" diameter by 0.92 thick
Through hole, 0.060 diameter
3
1"
2"R
0.750
60
45
30
1"R
0.750
Focal Point
1.75
Through hole, 0.060 diameter

(a) International Institute of Welding (IIW) block, type 1

(b) Miniature angle-beam block

Figure 32-2-14 Two standard reference blocks used in ultrasonic inspection: (a) International Institute of Welding (IIW), type 1, block; (b) miniature angle-beam block

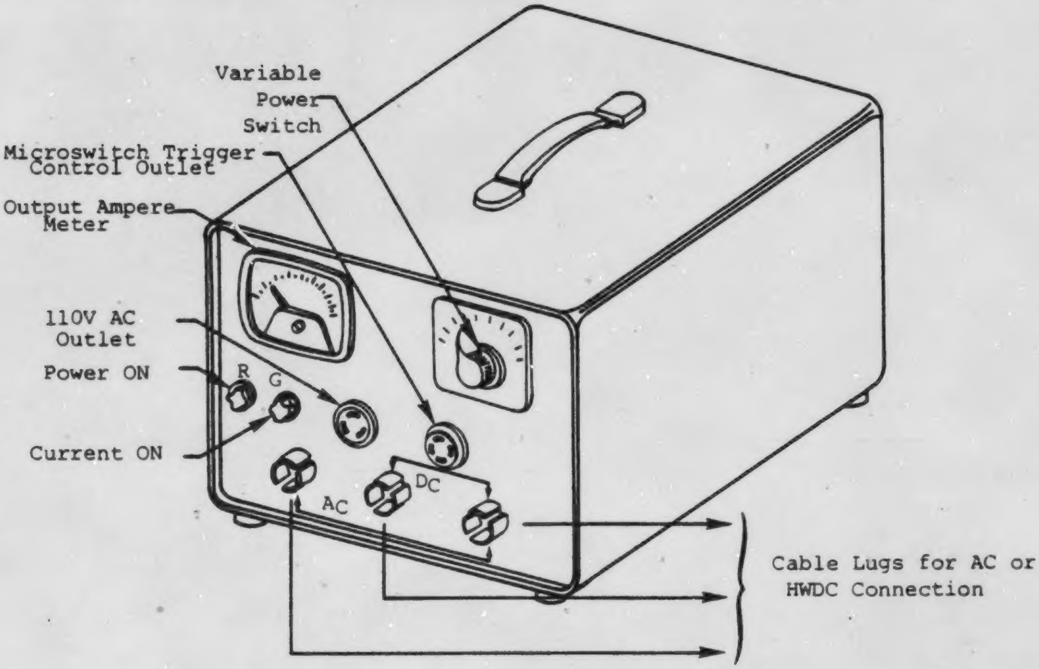

Variable Power Switch
Microswitch Trigger Control Outlet
Output Ampere Meter
110V AC Outlet
Power ON
R
G
Current ON
AC
DC
Cable Lugs for AC or HWDC Connection

Figure 32-3-20 Portable Magnetic Particle Power Unit

Prods may be of two different types, as illustrated in Figure 32-3-21.

1. Individual prods for each cable, with a remote control switch built into one of the prod handles. The switch is connected to the power unit microswitch outlet with a separate cable, and is used to activate a relay in the power unit which turns on the magnetizing current after the prods have been properly positioned on the test specimen. Or,
2. Dual-prod assembly, with fixed prod spacing, and remote control switch installed in the handle.

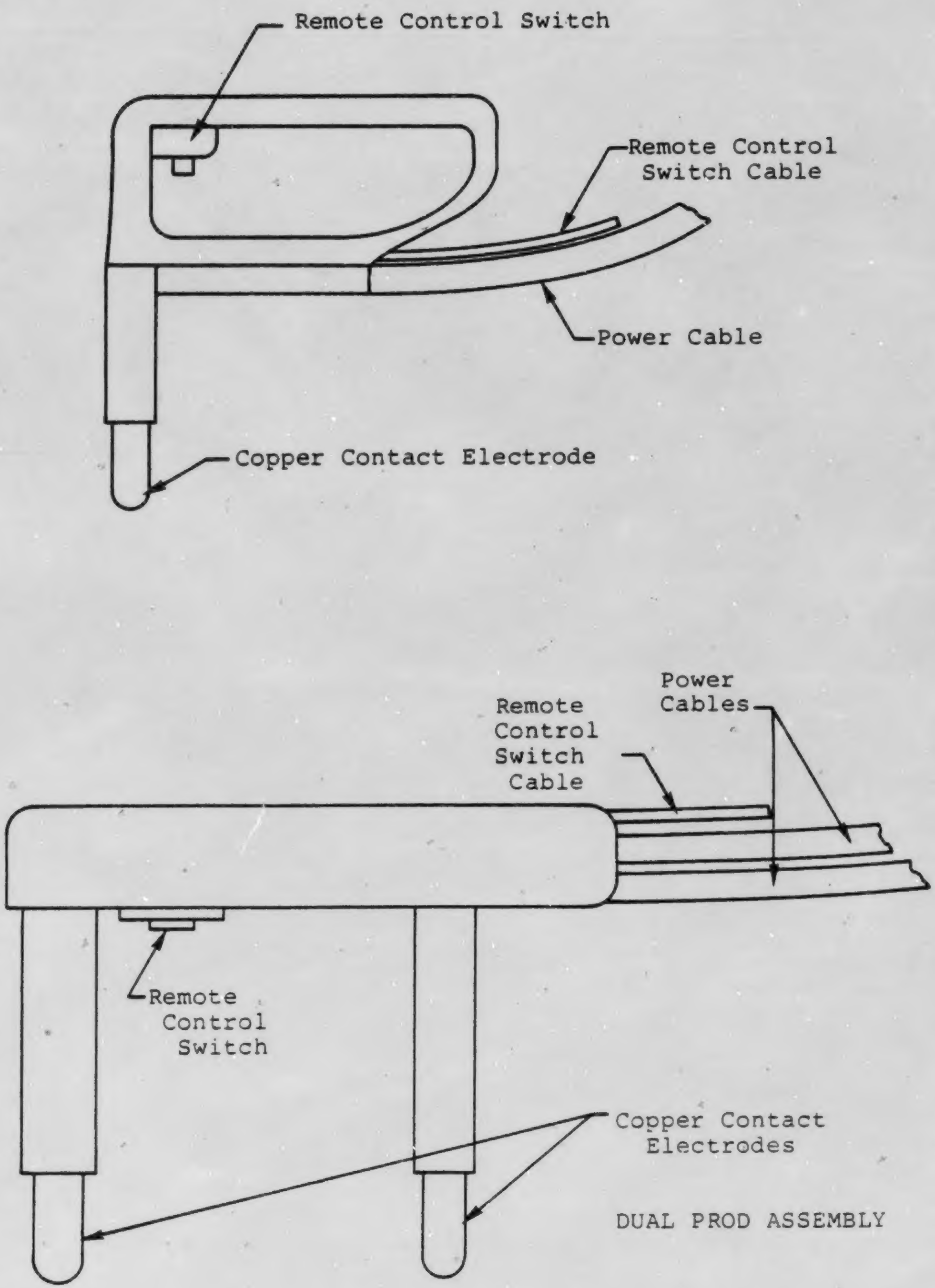

Remote Control Switch
Remote Control Switch Cable
Power Cable
Copper Contact Electrode
Power Cables
Remote Control Switch Cable
Remote Control Switch
Copper Contact Electrodes
DUAL PROD ASSEMBLY

Figure 32-3-21 Accessory Prods

Magnetizing/Demagnetizing Coils

"Coil" assemblies which operate with either AC or HWDC current may be used for magnetizing and demagnetizing shafts, axles, spindles, bolts, or other light parts. A typical coil, as shown in Figure 32-3-22, has a foot operated switch for continuous control by the technician.

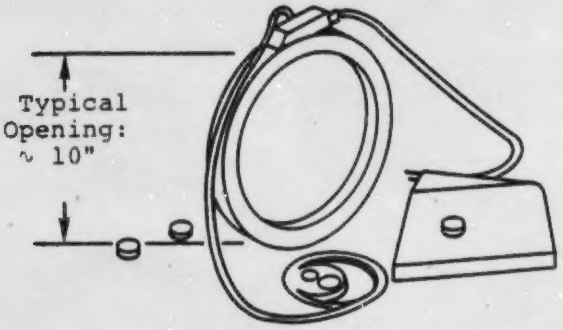


Figure 32-3-22 Magnetizing/Demagnetizing Coil

Cables

"Cables" used for carrying magnetizing currents in magnetic particle testing are usually made-up from heavy gauge rubber or neoprene covered welding cable. Such cables are constructed with soft annealed copper stranded conductors to provide maximum flexibility and minimum electrical resistance.

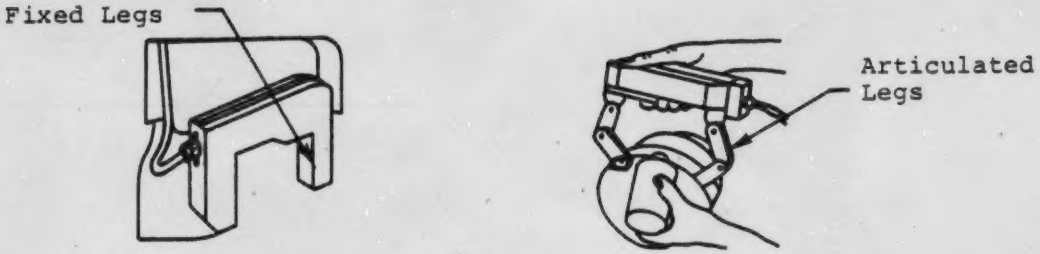
Magnetizing Yokes

"Yokes" are hand-held, "U" shaped magnetizing devices equipped with either a 110 volt ac electromagnet, or with alloy permanent magnets for generating a magnetic flux field. The openings between legs of typical yokes are approximately 5-6 inches.

Yokes produce flux fields of sufficient strength to locate surface discontinuities in welds, castings, and a variety of structures and parts.

Several types of yokes are illustrated in Figure 32-3-23.

Electromagnetic Yokes



Permanent Magnet Yoke

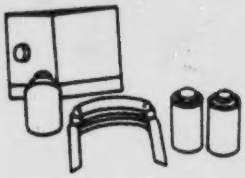


Figure 32-3-23 Magnetizing Yokes

Inspection Mediums

The selection of a suitable inspection medium is basic to the success of any magnetic particle test. The mediums used are non-toxic, metallic, or metallic oxide particles, free of contaminants, with four specific properties: magnetic, geometric, mobile and visible. Application of the mediums may be accomplished with the dry method or the wet method, depending on the characteristics of the test specimen and the type of discontinuities to be detected.

Properties of inspection mediums:

1. Magnetic

   The particles must exhibit maximum response in a magnetic leakage field, and thus must possess high permeability (easily magnetized). Low retentivity is also desirable for ease in removal of the particles from the specimen following the test.

2. Geometric

   The shapes and sizes of particles have a significant effect on particle mobility and attraction by leakage field. Spherical shaped particles have a high degree of mobility but low attractive power, while long slender particles have a high degree of mobility but low attractive power resulting from strong, induced magnetic fields. Small particles are required to indicate small, tight discontinuities, and to respond to weak leakage fields; larger sizes are more suitable for indicating wider or larger discontinuities.

3. Mobility

   When particles are applied to the surface of a magnetic specimen, they must be mobile or free to form patterns or indications at locations of leakage fields. This mobility is influenced by particle shape and size, field strength, specimen surface condition, and method of application.

4. Visibility

   Particles must be readily visible, or contrast sharply with the background, when they collect at a leakage field location and indicate a discontinuity. Powders used in the dry application method are usually coated with a red, black or gray color, and should be selected to provide maximum contrast on the particular specimen material. Particles used in the wet method may be red or black oxides, or coated with a dye which fluoresces brightly under ultraviolet or black light.

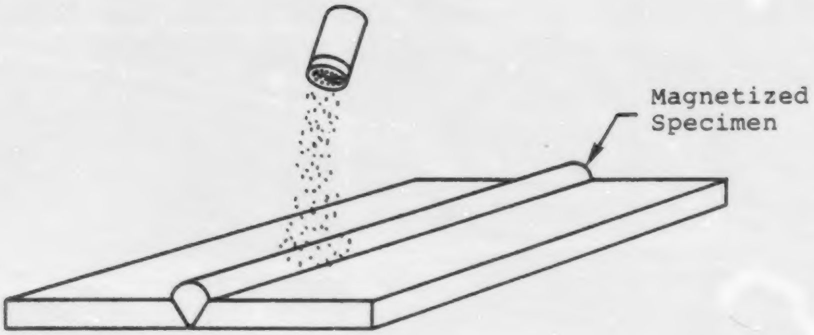
Application of Inspection Mediums:

1. Dry Method

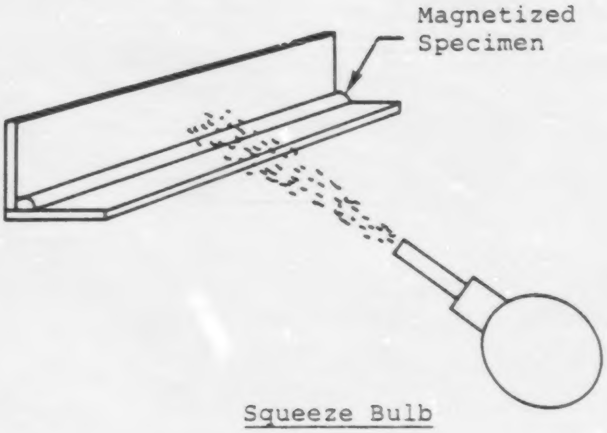
   Magnetic particles are normally applied to the specimen by dusting lightly from shaker cans or blowing from squeeze bulbs. The particles are floated down to the surface, permitting the leakage fields at discontinuities to attract and hold some of the particles as they move by. Following the application of the powder, the excess is removed with a gentle air stream. Methods of applying the dry powder are illustrated in Figure 32-3-24.

2. Wet Method

   Finely divided particles or iron oxide are suspended in a low viscosity petroleum distillate or water, and applied to the specimen either by spraying, flowing or brushing onto the surface, or by immersion. The particles used in the suspension may be colored red or black, or may be the fluorescent type which requires that the specimen be inspected under black light.


Magnetized
Specimen

Shaker Can


Magnetized
Specimen

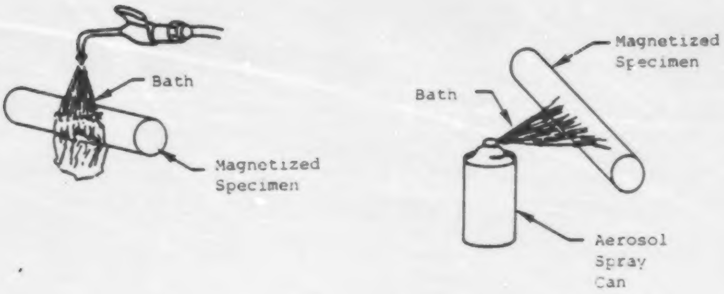
Squeeze Bulb

Figure 32-3-24 Particle Application - Dry Method

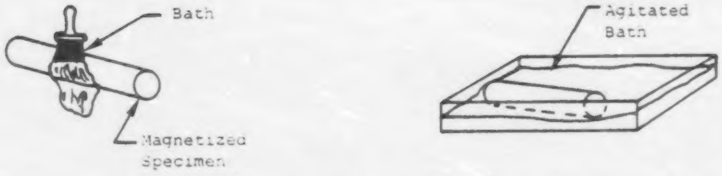
This method provides maximum particle mobility, and, due to the extremely small particle size, is well suited for detecting very small discontinuities extending to the surface of the specimen.

Test sensitivity is dependent on particle concentration in the bath, however, so proper preparation and maintenance of the bath is essential. The suspension should be agitated or circulated during use, and protected from contaminants.

Methods of applying the suspension are illustrated in Figure 32-3-25.


Bath
Magnetized Specimen
Magnetized Specimen
Bath
Aerosol Spray Can

Flowing Spraying


Bath
Magnetized Specimen
Agitated Bath

Brushing Immersion

NOTE: Magnetic particles are suspended in the bath, and applied to the surfaces of test speciments as illustrated.

Figure 32-3-25 Particle Application -- Wet Method

Stationary Equipment - Wet Method

Most magnetic particle inspection by the wet method is done with stationary type equipment such as that shown in Figure 32-3-26. Units of this type are complete testing systems for processing and inspecting parts. Typical units feature variable AC/DC power supplies, suspension reservoir tanks, suspension collection or drain tray, suspension circulating pumps, ultraviolet inspection lights, magnetizing and demagnetizing coils, and head stock/clamping assemblies for holding test specimens.

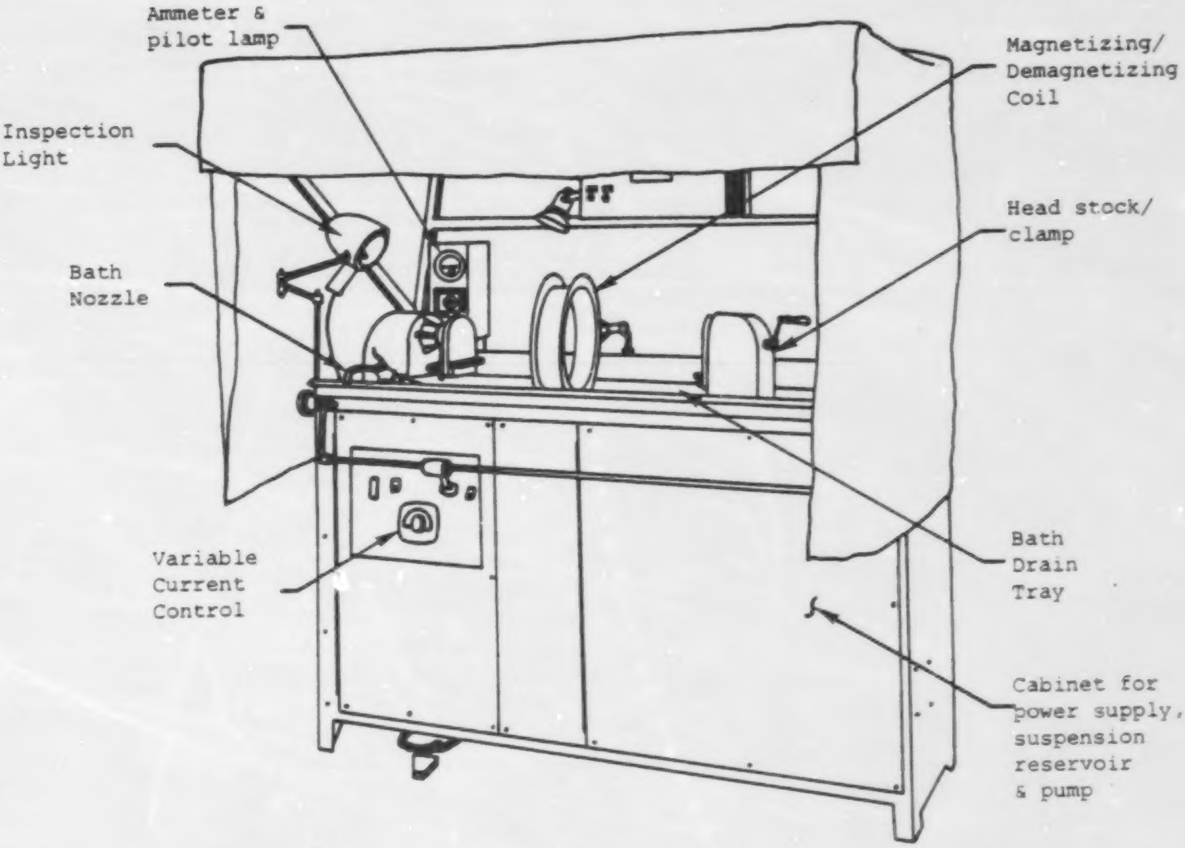

Ammeter & pilot lamp
Magnetizing/ Demagnetizing Coil
Inspection Light
Head stock/ clamp
Bath Nozzle
Variable Current Control
Bath Drain Tray
Cabinet for power supply, suspension reservoir & pump

Figure 32-3-26 Stationary Equipment - Magnetic Particle Testing, Wet Method

Ultraviolet Inspection Lights

When magnetic particle testing is done with the wet method and fluorescent particles, examination is performed under high intensity near ultraviolet (black) lights, provided with suitable clean filters which eliminate the short-wave length burning rays and pass most of the visible light. For general use, the measured light intensity at the surface of the specimen inspected is recommended to be 90 foot-candles.

A typical inspection light of this type is shown in Figure 32-3-27.

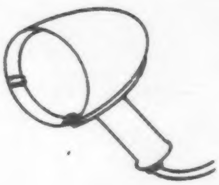


Figure 32-3-27 Ultraviolet (black) Inspection Light

Principles of Demagnetization

Some residual magnetism is usually retained by ferrous materials after being removed from the magnetizing force. The strength of the residual field is dependent on the permeability and retentivity of the material, and the strength and direction of the magnetizing force. The opposite magnetic force that is required to neutralize a residual field in ferromagnetic material, and return the material to its original nonmagnetic condition is called the coercive force.

Demagnetization is required when (a) the residual field may interfere with subsequent operations such as welding or machining, (b) the specimen is a moving part of an assembly and accumulated ferrous particles and chips could cause wear, or (c) the residual field could affect nearby instruments or controls.

It is extremely difficult to attain complete demagnetization, so an acceptable level is usually determined and defined, and the residual field reduced to that value.

Demagnetization of parts may be accomplished by subjecting the magnetized part to a continuously reversing magnetic field (Coercive force) which gradually decreases in strength. The residual field in the article can be quickly reduced to an acceptable level with this technique.

Demagnetization may be performed with either alternating current or direct current:

Alternating Current Demagnetization

The easiest method of demagnetization is to pass the magnetized part through a coil which is energized with alternating current. The induced field in the part is continuously reversed as the current reverses in the coil. As the part is withdrawn and removed further from the coil and its magnetic influence, the induced field in the part becomes weaker and weaker.

Direct Current Demagnetization

In order to demagnetize with direct current, the magnetizing equipment must be equipped with appropriate controls for fine, incremental current reduction and current reversal. With such controls demagnetization can be performed more effectively than with alternating current.

The procedure to be used is to place the part in a coil and adjust the current to a value equal to or greater than that used to magnetize the part; then stop the current flow, readjust the current to a lower value, reverse the direction of flow, and give the part a "shot" of current at this setting. This procedure of current reversal and reduction is continued until the lowest adjustable value is reached, usually in 25 or more small, incremental changes.

Demagnetization may not be required for specimens such as large weldments or vessels where residual fields have no detrimental effect, or for specimens to be heat treated, for when ferromagnetic materials are heat treated, the curie point is usually surpassed (e.g., the temperature at which magnetic materials lose their residual magnetism).

Applicability of Magnetic Particle Test Methods

The two basic magnetic particle test methods, the dry method and the wet method, differ in the test medium particle size, and the relative particle mobility characteristics.

The dry method is particularly well suited for inspecting large parts such as casting, forgings and weldments with local circular magnetism induced directly with prods. The dry powder technique is more sensitive in detecting near surface discontinuities than the wet method, but is less sensitive in detecting fine, surface discontinuities. The dry method is most convenient for use in field inspection work and for inspecting large areas due to the simplicity in equipment requirements (a means of inducing a magnetic field, and a means of dusting on powder).

Typical discontinuities which may be detected with the dry method are:

- surface flakes in forgings
- fatigue cracks in parts in service
- shrinkage cracks in castings and in welds
- tears in castings
- porosity or sub-surface sand in castings
- unfused chaplets in castings
- sub-surface cracks and inclusions in welds
- lack of fusion in welds
- plate laminations

The inspection medium used in the wet method consists of extremely small particles, on the order of a few microns in size, suspended in a low viscosity liquid for maximum particle mobility. This medium is very sensitive to weak leakage fields, and is well suited to the detection of very fine discontinuities extending to the surface, such as grinding cracks and fatigue cracks.

The wet method is usually used for inspecting smaller parts, such as aircraft, automotive, or machine parts, where stationary equipment is available. In most cases, the entire part can be magnetized, and the indicating medium flowed easily over all surfaces; or the part is immersed in the indicating suspension bath. With the use of the stationary equipment, the excess suspension material is collected in a reservoir and reused, with very little material loss. Contrasting color particles may be used in the bath, or fluorescent particles may be used which require inspection under black light.

Many items are inspected automatically with fully-automated production line equipment, using wet method magnetic particle defect detection and laser scanning techniques. Such systems are used in the manufacture of steel mill products, and automotive, aviation and railroad products.

In some cases, large precision machined parts, such as shafts, are inspected with the wet method, usually with fluorescent type particles, in examining for stress or fatigue cracks.

Advantages and Disadvantages of Magnetic Particle Test Methods

In general, the advantages of magnetic particle inspection are:

- the method can be used on any specimen made of ferromagnetic material
- the method can be utilized almost anywhere with portable equipment
- the method is a positive means of detecting surface or near-surface defects
- personnel are easily trained to operate equipment & interpret results
- test equipment and materials are relatively inexpensive

Some of the limitations and disadvantages of the test method are:

- method is applicable only to magnetic materials
- pinpoint inclusions are difficult to locate
- hairline cracks are hard to locate, and may be overlooked if they happen to line-up with the magnetic lines of force

- false indications of defects can result from:
  - abrupt changes in permeability of the specimen material
  - junctions of different metals (different permeability)
  - cold working of some metals (change in permeability)
- subsurface defects in welds such as slag inclusion, lack of fusion, lack of penetration, porosity and internal shrinkage cracks cannot be detected much beyond 0.25 inches below the surface
- laminations in plate cannot be detected unless the leakage field penetrates to the surface (which normally happens only at the plate edge)
- false indications can occur from careless handling of parts, or dragging one part across another after magnetizations. Blurred line indications are produced on the surfaces of the parts, and are known as "magnetic writing"
- use of prods in applying magnetizing current can produce arcing and burns detrimental to the specimen, leading to ultimate failure in service.

EXERCISES

1. Indicate whether the following statements are true or false:

___ a. Uniform alignment of molecules usually occurs in magnetized materials.

___ b. A magnetic field in a magnetic material is also known as magnetic flux.

___ c. The "right hand rule" is a simple procedure for determining magnetic field strength.

___ d. The magnetic field produced by a coil decreases in strength as additional loops are added to the coil.

___ e. The magnetic field in a bar magnet will be destroyed when the magnet is broken in half.

2. Complete the following statements by filling in the blanks:

a. The magnetic force field surrounding a bar magnet is concentrated at the ____________.

b. A property of magnets is that __________ poles repel, and _______________ poles attract.

c. A __________ magnetic field always surrounds a conductor carrying an electric current.

d. A __________ magnetic field is produced within a current-carrying coil.

3. Match the correct word with the statement:

a.	Materials repelled by magnetism	___	(1)	reluctance
b.	Materials attracted by magnetism	___	(2)	coercive force
c.	Resistance to magnetizing force	___	(3)	magnetic flux
d.	Demagnetizing force	___	(4)	diamagnetic
e.	Easily magnetized material	___	(5)	residual field
f.	Maximum magnetic field strength	___	(6)	paramagnetic
g.	Lag between magnetizing force and flux density	___	(7)	retentivity
			(8)	hysteresis
			(9)	permeable
			(10)	saturation

4. Indicate whether the following statements are true or false:

___ a. A magnetized material with low permeability usually will have high residual magnetism.

___ b. A high coercive force is required to remove a residual field from highly permeable material.

___ c. Usually the same amount of current is required to remove the residual magnetism from a specimen, that was used to initially induce the field.

___ d. A magnetic field in magnetically saturated material can be doubled by doubling the magnetizing current.

5. Complete the following statements:

a. Surface or near surface discontinuities in magnetized ferromagnetic materials produce __________ __________ which will attract magnetic particles.

b. Diffused indications are usually produced by __________ defects.

c. Internal discontinuities, either deep or lying __________ to the surface, are very difficult to detect.

d. A leakage field develops when a __________ is interrupted.

6. Complete the following statements:

a. The two types of current most used for inducing magnetic fields in test specimens are __________ and __________.

b. __________ can be easily stepped up or stepped down in voltage with transformers.

c. __________ may be used to induce a pulsating, deeply penetrating magnetic field in a test specimen.

d. Magnetizing a part by passing an electric current through the part is called __________.

e. The use of a central conductor in magnetizing a hollow test specimen produces a __________ magnetic field in the part.

f. Permanent magnet yokes are most useful for detecting __________ discontinuities.

g. The use of prods in magnetizing a test specimen produces a __________ field.

h. Electromagnetic yokes produce __________ flux fields.

i. Discontinuities in a test specimen will not be detected unless they cross __________.

j. The strong magnetic field produced on the surface of a part by the use of alternating current for direct induction is called the __________.

7. Indicate true or false for the following:

___ a. Half-wave rectified current is best suited for locating surface defects.

___ b. The pulsating characteristic of half-wave rectified current improves magnetic particle mobility.

___ c. A rectifier permits current to flow in one direction only.

___ d. Alternating current is not suitable for locating deep, sub-surface discontinuities.

___ e. Longitudinally oriented defects are best found by inducing a longitudinal field in the part.

8. Indicate true or false for the following:

___ a. Magnetic particle power units usually have variable power outputs for both alternating current and half-wave rectified current.

___ b. Prods are used for the direct induction of magnetizing current in test specimens.

___ c. Due to high electrical resistance, welding cable cannot be used for carrying magnetizing currents.

___ d. Yokes are useful for inspecting for surface defects.

___ e. Non-magnetic particles are always used as inspection mediums in magnetic particle testing.

___ f. Fluorescent magnetic particles fluoresce brightly under infra-red light.

___ g. For maximum test sensitivity in magnetic particle inspection, the inspection medium should be applied heavily, and heaped upon the test surface.

9. Complete the following statements:

a. Demagnetization is required to remove __________.

b. Demagnetization may be accomplished by heating a magnetized part to its __________.

c. The easiest method of demagnetization is to pass the part through a coil energized with __________ current.

d. The strength of a residual field is dependent on the material __________ and __________.

e. It may be necessary to use the __________ current method of demagnetization to eliminate a residual field in a large forging.

f. In demagnetizing a large, heavy part, the current must be __________ and __________ in small, incremental steps.

10. Indicate True or False for the following statements:

___ a. The dry method is best suited for detecting fine, surface discontinuities.

___ b. The dry method is usually used for inspecting large weldments.

___ c. Stationary magnetic particle inspection equipment is usually used for examining small parts with the wet method.

___ d. Aluminum aircraft parts are usually inspected with the dry powder magnetic particle method.

___ e. The wet method with fluorescent type particles provides maximum particle contrast and mobility.

MATERIALS

The subject material contained in this module may be taught without using actual test equipment, materials, and specimens, but the availability of the items listed below to the student/trainee is highly recommended:

1. Portable or mobile power supply unit, with variable outputs for HWDC and AC current.
2. Portable, electromagnetic yoke (110v. AC type)
3. Portable, permanent magnet yoke
4. Black light inspection lamp
5. Inspection media:
   - Red & black dry powders
   - *Red wet-bath suspension powder and solvent
   - *Fluorescent wet-bath suspension powder and solvent
6. Demagnetizing coil (110 v. AC type)
7. Inspection media applicators
   - Dry powder squeeze bulb
   - Wet-bath hand sprayer
8. Light meter for checking black light lamp output.
9. Test specimens with typical defects or discontinuities.

* These materials may be obtained pre-mixed and packaged in aerosal cans.

PROCEDURES

1. Tour a magnetic particle test facility. Note power unit, test media, coils, yokes, prods, and wet or dry method and discuss notes in class.
2. Witness a magnetic particle test demonstration. Note type of current, particle application and inspection and discuss notes in class.

DATA TABLE

None.

REFERENCE MATERIALS

Betz, C.E., Principles of Magnetic Particle Testing, Magnaflux Corporation, Chicago, Ill.

Libby, Hugo L., Introduction to Electromagnetic Nondestructive Test Methods, 1971, Wiley-Interscience

McGounagle, Warren J., Nondestructive Testing

Metals Handbook, Volume 11, Nondestructive Inspection and Quality Control, American Society for Metals

Nondestructive Testing Handbook, edited by Robert C. McMaster, Ronald Press, 1959.

TEST

1. Sketch a permanent bar magnet, label its poles, and indicate the magnetic flux field pattern.

2. Describe the effect on magnetic fields by material discontinuities which makes possible detection of such discontinuities by magnetic particle testing.

3. Differentiate circular and longitudinal magnetic fields.

4. Define:
   a. residual magnetism

   b. coercive force

5. Name two types of current frequently used in magnetic particle examination and describe their relative penetrating capability:
   a.

   b.

6. Describe how an object is magnetized by a coil and state if the resultant field is circular or longitudinal

7. Describe or sketch the physical arrangements of a yoke and state its application.

8. Describe a "head shot" and state if the magnetic field is circular or longitudinal.

9. Describe or sketch direct induction prods and state its application.

10. State the application of central conductor magnetization and whether induced fields are circular or longitudinal.

11. Differentiate a mobile power unit and a stationary power unit.

12. Name four properties of concern with respect to magnetic particles and briefly describe desirable characteristics of each.

13. Briefly describe the dry method of application of magnetic particle inspection medium.

14. Briefly describe the wet method of application of magnetic particle inspection medium.

15. State the purpose of ultravoilet inspection lamps with respect to magnetic particle examination.

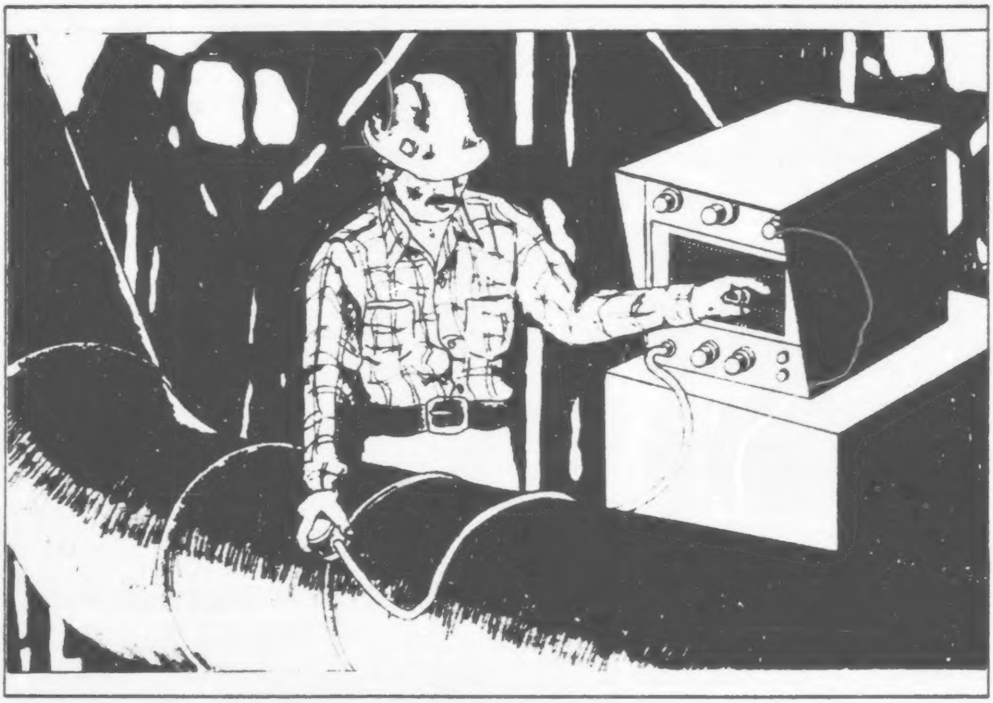
16. State four advantages of the magnetic particle test method.

17. State four disadvantages of the magnetic particle test method.

NUCLEAR TECHNOLOGY

MODULE 32 - 4

OPERATION OF MAGNETIC PARTICLE TEST EQUIPMENT



COURSE 32: NONDESTRUCTIVE EXAMINATION (NDE)

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

MODULE 32-1	Fundamentals of Ultrasonic Testing
MODULE 32-2	Operation of Ultrasonic Test Equipment
MODULE 32-3	Fundamentals of Magnetic Particle Testing
MODULE 32-4	Operation of Magnetic Particle Test Equipment
MODULE 32-5	Fundamentals of Eddy Current Testing
MODULE 32-6	Operation of Eddy Current Test Equipment

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INTRODUCTION

The Nuclear QA/QC Technician can have duties which require him or her to qualify as a Level I or Level II magnetic particle inspector. Such qualification requires the ability to operate magnetic particle equipment in accordance with written procedures.

Magnetic particle testing is an extremely useful and relatively simple means of examining ferromagnetic materials for a variety of discontinuities. This module describes the specific technique variables and options which are available to the test technician, provides instructions for selecting and operating the appropriate test equipment, describes physical criteria for detectable discontinuities, defines and describes non-relevant indications, and describes specific types of relevant discontinuities which require detection, interpretation, and evaluation.

MODULE PREREQUISITES

The student/trainee should have prior training or experience on fundamentals of magnetic particle testing. Completion of Nuclear Technology, Module 32-3, Fundamentals of Magnetic Particle Testing, satisfies this prerequisite.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Successfully complete a written examination which consists of questions selected from the Level II SNT-TC-1A certification written test.
2. Demonstrate a knowledge of magnetic particle test equipment operation by inspecting selected parts.
3. List typical discontinuities found in various materials resulting from inherent, processing and service defects, and describe the corresponding indications produced from magnetic particle examination.
4. Describe appropriate magnetic particle tests as listed below for different test specimens with known defects:
   a. magnetization with prods, dry particle method
   b. magnetization with coil, wet particle method
   c. magnetization with yoke, dry particle method
   d. magnetization with prods, wet fluorescent
5. Select for each test in objective #4 the appropriate test equipment, calculate current requirements, adjust equipment properly, induce magnetic field correctly, apply test medium in recommended manner, and evaluate test indications.

SUBJECT MATTER

MAGNETIC PARTICLE TESTING TECHNIQUE VARIABLES

Scope

Many variations in testing techniques are available to the technician or inspector, and must be evaluated before beginning a test. The technique selected must be appropriate for the test specimen and types of test equipment available. In addition, the technique must assure adequate sensitivity and reliability. With regard to the test specimen, the specimen size and shape, type of ferromagnetic material, and type of defects sought must be considered.

The variations which require evaluation include:

- Type of current - The type of current is limited by the equipment available. Most equipment has output terminals for alternating current (AC) and for half-wave rectified single phase direct current (HWDC). Also, equipment may be available which supplies three phase rectified direct current or rectified and filtered current which is direct D.C.
- Type of particles and method of application - Magnetic particles may be applied by the dry method or the wet method. Particles may be colored or fluorescent, the type of particles must be compatible with the method of application and equipment.
- Sequence of steps - Particles may be applied by the continuous method which is concurrently with the application of te magnetizing force. Particles may be applied by the residual method, which is after the current has been turned off.
- Direction of field - The type of magnetic field, such as circular or longitudinal, should be appro-

priate for the configuration of the specimen. The methods and locations of making contact or using a coil are to be considered.

- Sensitivity - The sensitivity of the test is governed by a combination of factors: magnetizing force intensity, test medium characteristics, method of application, specimen configuration, and surface finish and condition.
- Equipment - Type of power unit, prods, coils, yokes and other equipment must be selected such that the correct test with proper sensitivity is conducted.

Magnetizing Current and Magnetic Particle Application

The two basic decisions which must be made by the technician or inspector before selecting specific types of test equipment are the (1) type of current to be used, and (2) type of magnetic particles to be used. Table 32-4-1 lists the general types of defects sought, and in the order of preference, the recommended types of magnetic particles and current.

In determining the method and sequence of magnetic particle application, the type of material must be considered along with the characteristics of the residual method and the continuous method.

Residual Method

The residual method can be used only on materials with sufficient retentivity to produce leakage fields at discontinuities. Hard materials which have high retentivity usually are low in permeability and require very high magnetizing fields to produce satisfactory results. When the magnetizing force is removed from a part, the residual magnetism in the part is always less than the field present when the force was acting. The amount of

Table 32-4-1 List of Defects and Recommended Magnetic Particle/Magnetizing Current Types

Type Defect Sought	Type Magnetic Particles	Type Magnetizing Current
Very fine, shallow, surface defects	1. Wet method, fluorescent 2. Wet method, non-fluorescent 3. Dry powder	1. A.C. 2. HWDC
Coarse surface defects	1. Dry powder 2. Wet method	1. HWDC 2. 3-phase rectified A.C. 3. Straight D.C. 4. A.C.
Sub-surface	1. Dry powder	1. HWDC 2. 3-phase rectified A.C. 3. Straight D.C.

magnetic field loss depends on the retentivity of the material.

Continuous Method

The continuous method provides greater sensitivity than the residual method, because the magnetic particles are applied when the magnetic field is at maximum strength. Maximum sensitivity can be obtained for very fine defects by immersing the part in a wet bath, passing the magnetizing current through the part for a short time while immersed, and allowing the current to remain on while the part is withdrawn from the both for draining. When immersion is not practical due to the size of the part, the wet bath can be sprayed on and allowed to drain off while the current is on.

Direction of Field

The next variable that must be evaluated by the technician is the direction of the magnetic field. In order for a discontinuity to produce a visible indication, it must intersect (cross) the magnetic lines of force. If the discontinuity lies parallel to the flux lines, a magnetic polar condition, which will attract magnetic particles, will not be established, and an indication will not be produced. In most cases, it is recommended that each specimen be magnetized twice (in different directions) during the examination in order that all possibly present discontinuities may be located. Fields are advised by either the circular or longitudinal method.

Circular Magnetization

Of the two types of magnetization, circular is frequently preferred because it produces a minimum of external polarity that can attract and hold particles where no discontinuity exists. When passing a current through a specimen to produce a circular field, it should be remembered that discontinuities which are roughly parallel to the current (perpendicular to the magnetic field) will be detected. Those which are perpendicular to the current may not be detected.

The strength of the magnetizing current used on any specimen should not exceed the value needed to produce indications of the discontinuities which are sought. The required current values for circular magnetization vary because of differences in alloys and shapes. For regularly shaped parts (such as bars, rods, cylinders, etc.), the rule of thumb is to use the following current values:

- When using half-wave D.C., use from 800-1000 amperes per inch diameter or cross section.

- When using A.C., use 500-600 amperes per inch diameter or cross section.

These values may be used whether the parts are magnetized by passing the current directly through the part, as in a "head short", or by placing a hollow part (or a part with a hole) on a "central conductor". Approximate magnetizing current values for these type of specimens are listed in Table 32-4-2.

Table 32-4-2 Magnetizing Current, Circular Method, for Solid and Tabular Specimens

Greatest Width or Diameter, In Inches	Magnetizing Current In Amperes (Max.)	
	HWDC	AC
1/2	500	300
3/4	750	450
1	1000	600
1 1/2	1500	900
2	2000	1200
2 1/2	2500	1500
3	3000	1800
3 1/2	3500	2100
4	4000	2400

When testing is performed on many similar parts, such as in a manufacturing operation, a "standard", or test specimen with a typical indication should be used for reference and checked from time to time. The "standard" may be used to adjust the current to obtain optimum sensitivity to the types of discontinuities which are sought.

Longitudinal Magnetization

Longitudinal fields may be induced in small parts using fixed coils, but for large specimens, coils of heavy electrical cable (such as welding lead cable) are wrapped around the part. The effective magnetic field created in the part is determined by the product of the number of amperes and the number of turns in the coil (ampere-turns). For example, a 6 turn coil carrying a current of 1,000 amperes produces a magnetizing force of 6,000 ampere-turns.

Effective coil magnetization is also dependent on the specimen shape and in particular, the relationship of the specimen's length to its diameter. This relationship is known as the length/diameter (L/D) ratio of the part. Generally, the longitudinal axis of the part must be parallel to the magnetizing force, and the L/D ratio must be between 2 and 15. For example, a bar to be tested is 18" long and 6" in diameter. The L/D ratio is 18/6, or 3. This is an acceptable ratio for coil magnetization. In most cases, the area to be examined at one time should be limited to 18".

When a fixed coil is used, the specimen should be held against the inside wall of the coil and not positioned in the center of the coil. A maximum flux field is produced in the part when the cross-sectional area of the part does not exceed 1/10 the area of the coil operating.

The rule of thumb for calculating the required ampere for coil magnetization, longitudinal method, is represented by equation 32-4-1.

$$\text{Amperes} = \frac{45{,}000}{(L/D)} \times \frac{1}{T}, \text{ or } \frac{45{,}000\,D}{LT} \qquad \text{Equation 32-4-1}$$

Where:

45,000 = Constant
L = length of specimen
D = diameter of specimen
T = number of turns in the coil

Example

Problem: Determine acceptability of longitudinal magnetization and value of magnetizing current.

Given: A test specimen is 15" long and 5" in diameter. A coil is available consisting of 10 turns. The various values, then, from the equation 32-4-1 are:

45,000 = Constant
L = 15"
D = 5"
T = 10

Solution

The L/D ratio = 15/5 = 3, which is acceptable for coil magnetization. The required amperage, then, is calculated as follows:

$$A = \frac{45{,}000\ (5")}{(15")\ (10\text{ turns})} = \underline{\underline{1500\text{ amperes}}}$$

When inspecting a multiple-diameter specimen, it is recommended that the part be first magnetized with a current value as calculated for the smallest diameter of the part and inspected. The current required for the next larger diameter should then be calculated, and the part re-magnetized and that value and re-inspected. The part should be inspected in this manner once for each significant different part diameter, to assure proper field strength and test sensitivity in all areas of the specimen.

Prod Magnetization

Prod magnetization is a method of producing a circular field in a part, but the resultant field is actually distorted-circular, due to the poles created at the contact points. It has been shown in practice that prod spacing should usually be maintained between 2 and 8 inches. When inspecting plate-type materials, the current values shown in Table 32-4-3 usually produce satisfactory results. For inspecting large specimens, the rule of thumb is to use approximately 200 amperes per inch of prod spacing as a starting value. If the initial setting produces an excessive accumulation of particles between the points of the prods, the field strength is too great. In this case, either the current should be lowered, or the prod spacing should be increased.

Table 32-4-3 Recommended Prod Spacings and Current Values

Prod Spacing, Inches	Section Thickness, Inches	
	Under 3/4 inches	3/4 inch and over
2 to 4	200 to 300 Amperes	300 to 400 Amperes
>4 to <6	300 to 400 Amperes	400 to 600 Amperes
6 to 8	400 to 600 Amperes	600 to 800 Amperes

SELECTION AND OPERATION OF TEST EQUIPMENT

Scope

The various types of equipment most used for magnetic particle examination involve sections of power, units, prods, coils, yokes, and ultraviolet lamps. Characteristics of these items and techniques for their use are described in this section.

Power Units

Power units are used to provide the magnetizing current for testing with the coil, direct induction, or central conductor magnetizing techniques. The typical power unit consists basically of a step-down transformer, rectifier, and current off-on switching devices. Low voltage output is utilized to assure operator safety and to minimize arcing at contact points on the test specimen. Most units have variable power outputs. Typical portable power supplies have a range of about 100 to 1,000 amperes. Large units are available in many sizes, and may be designed to produce upwards of 20,000 amperes of current output.

There are three basic types of power units: the portable unit, the mobile unit, and the stationary unit. Each of these units usually has the following features:

- power on-off switch (power supply to unit)
- adjustable output (test) current control
- output (test) current ampere meter
- output terminals for AC current and some form of DC current (HWDC, straight DC, 3 phase rectified DC, etc.)
- switching device or connection for microswitch leads for switching output (test) current on and off

The portable units and mobile units are readied for service by (1) attaching the cable leads (for the coil or prods) to the appropriate output terminals, (2) connecting the microswitch leads to the unit, and (3) connecting the unit to the electrical service supply. When the unit is switched on, it is ready to operate. Before attempting to magnetize a part, the operator should check the operation of the unit to verify that it is operating satisfactorily. This may be done by (1) touching the prods together (if prods are used) or checking to be sure that the coil is connected, (2) depress the microswitch (which is sometimes located in one of the prod handles), causing current to flow, and (3) observing the output current meter for a meter reading which is representative of the output current setting. If a steady indication is obtained without fluctuation or erratic operation, the electrical connections are apparently properly secured and the equipment is ready for use. The operator then adjusts the output current control to the value needed to magnetize the particular part, and proceeds with the test.

Stationary units may be standard manufactured testing units, or custom manufactured units designed to test particular types of specimens. The typical stationary unit is capable of magnetizing specimens ranging from a few inches to 5 or 6 feet in length. Most stationary units are equipped with adjustable "head stocks" for clamping and holding specimens. The "head stocks" are actually integral electrical conductors or electrodes which contact the specimen and provide the electrical connection for passing a magnetizing current through either the specimen or a control conductor. Separate cables to coils or prods usually are not used with stationary units.

Stationary units are usually designed and equipped to use primarily the wet bath inspection method. As such, each is equipped with a reservoir for the inspection media (fluid), and pumping device, and a hose and nozzle used for flowing the liquid onto the specimen.

A magnetizing/demagnetizing coil is generally included as an accessory on most stationary units. The electrical controls on the unit are usually arranged so that the coil may be energized with either A.C. or D.C. current, as selected by the operator.

Some of the other features, which may be included on stationary units, and their functions, are listed in Table 32-4-4.

A test is normally conducted on a stationary unit as follows:

- Turn main power switch on the energize unit.
- Turn on inspection-bath pump and agitator. Allow the inspection-bath liquid to mix and circulate for approximately 10 minutes (or as recommended by the equipment manufacturer) prior to using for inspection. The inspection-bath is a suspension of very fine magnetic particles in a liquid vehicle, usually light oil or kerosene. To achieve the required test sensitivity, the degree of particle concentration must be correct, and should be checked daily before testing begins. The bath is usually checked by performing a settling test. This is done by pumping a small representative sample (about 100cc) of the suspension into a graduated centrifuge tube, allowing the particles to settle, and observing the quantity in the tube. The recommended concentrations for these wet suspensions, as measured on a 100 cc sample by a settling test are:

Table 32-4-4 Typical Stationary Power Unit Features

Feature	Function
• DC Pilot Light	Indicates DC output current
• AC Pilot Light	Indicates AC output current
• Block Light	Fluorescent particle inspection technique
• Hood and Curtain	Encloses unit and operator, to allow "black light" inspection
• Demag Current Pilot Light	Indicates demagnetization output current
• AC Transfer Switch	Selection of head stock contacts or coil connection for AC output current
• Timed Magnetizing Current Control	Applies timed magnetizing current
• Automatic Demag Cycle Control	Provides automatic coil demagnetization
• DC Transfer Switch	Selection of bead stock contacts or coil connection for DC output current
• DC-AC Selector Switch	Operates current-type selection
• Control Cable Connection	Connection for external control switch
• 110 VAC Outlet	Convenience outlet
• Line Pilot Light	Supply voltage indicator
• Pump Switch	Control inspection bath pump
• AC Ammeter	Indicates strength of AC output current
• DC Ammeter	Indicates strength of DC output current
• Magnetizing Current Pilot Light	Indicates when magnetizing current is on

- Nonfluorescent particles - 1.7-2.4 cc particles/100cc
- Fluorescent particles - 0.2-0.5 cc particles/100cc
- Set AC-DC current selector switch as required.
- Set current transfer switch to feed power to either the heat stocks or the coil, as selected for the test.
- Set the test specimen in place for testing by either (1) clamping in between the head stocks, (2) placing on a central conductor, clamped between the head stocks, or (3) placing in the coil with the ends resting on the support ledges of the head stocks.
- Set the current control at the proper amperage setting.
- Set the magnetizing current timer (if applicable).
- Apply the magnetizing current by activating the control switch.
- If the continuous method is used, flush the wet bath (inspection media) over the part while the magnetizing current remains on.
- If the residual method is used, flush the wet bath over the part after the magnetizing current has been started and stopped.
- The specimen is now examined for discontinuities.
- Following the examination for discontinuities, it is recommended that the specimen be re-magnetized in another position or another direction, and re-inspected.

Prods

Prods, whether individual prods or the dual-prod assembly type, are equipped with heavy power cables and a remote control switch cable. Prods are usually used only with portable or mobile power units. When the power cables are connected to the selected output terminals, and the remote control switch cable is connected to the control outlet on the power unit, the prods are ready for use. Before beginning a test, it is customary to check the equipment for proper operation. This may be done by (1) turning power unit "ON", (2) touching prods together, or touch both electrodes to a piece of steel or other conductive material, and (3) observe the output ampere meter for a steady current-flow indication when the remote control switch is depressed.

After checking the equipment, the technician may proceed with the test in the following steps:

- Examine the specimen for size and shape.
- Set the power unit for the recommended output current.
- Magnetize the specimen by pressing the prod trips on the specimen at the appropriate locations (while maintaining proper spacing), and pressing the trigger or remote control switch to turn on the magnetizing current.
- Apply the magnetic particles by either the continuous or the residual magnetism method (the continuous method is usually preferred for the large specimens and for the inspection of welds.)
- Examine for discontinuities.
- Re-examine the same area by re-magnetizing in a different direction (by rotating the prod locations about 90° and re-examining to assure that all discontinuities are indicated.)

Coils

Coils may be used for both magnetizing and for demagnetizing parts, and may be one of several types:

- Fixed AC current coils, which plug directly into a 110 VAC receptacle
- Fixed AC or DC coils mounted on stationary power units
- Fixed AC or DC coils, with cable leads for use with portable or mobile power units
- Coils formed by draping or wrapping cable turns around a specimen

For magnetizing parts, coils work most effectively on specimens whose cross-sectional area is about 1/10 the area of the coil opening or less. For a typical fixed coil of approximately 10" diameter opening, therefore, it would operate most effectively on specimens up to about 3" in diameter. When this relationship of specimen diameter to coil diameter is exceeded, a coil formed with cable turns should be used. This method of forming a coil is illustrated in Figure 32-4-1.

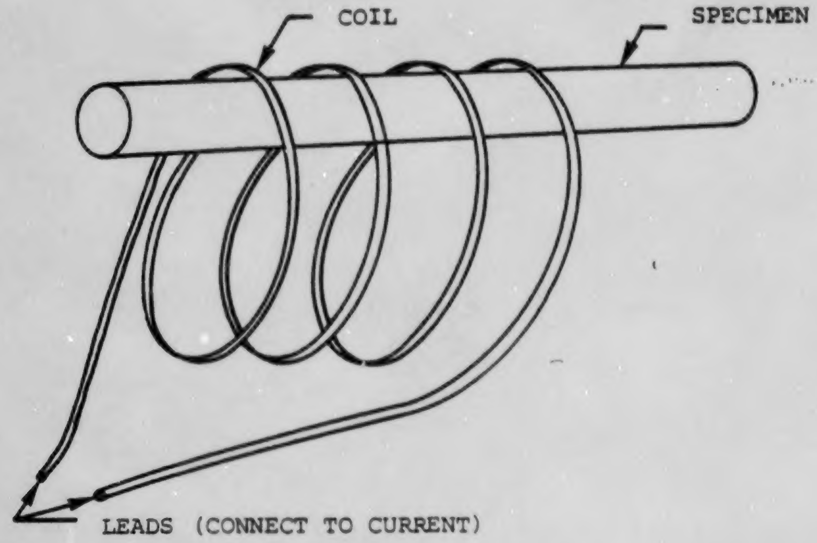


Figure 32-4-1 Cable-Type Coil

Coils are used in performing magnetic particle tests in the following manner:

- Connect coil to power source.
- Position the specimen in the coil, with the specimen touching the coil on one side.
- Examine the specimen and calculate the required amperage (considering part size and number of coil turns), when a variable power source is used, and set the proper value on the power unit current control. (There is no adjustment for fixed coils which plug directly into 110 VAC.)
- Energize the coil, and magnetize the specimen.
- Apply the magnetic particles by either the continuous or the residual magnetism method.
- Examine for discontinuities.

Any of the coils mentioned above can also be used for demagnetizing parts. The basic method of reducing or eliminating a residual magnetic field in any specimen is to subject the specimen to a continuously reversing magnetic field which gradually reduces in strength. This procedure causes a corresponding reversal and reduction of the field in the specimen.

The simplest and most convenient method of demagnetization is to use the fixed AC coil. With this method, the part is slowly passed through the energized coil and withdrawn from its influence. Since the direction of the current flow in the coil reverses itself continuously, the field in the specimen is also reversed, and as the part is moved away from the coil, the field is reduced to an insignificant level. The only drawback to this method is the fact that since AC current does not produce a deeply penetrating magnetic field, the method usually is effective only for small parts.

Large, heavy, or unusually shaped specimens can be demagnetized with the other types of coils, using DC current, if the power unit has provisions for very fine current control and a switching device for reversing the current. If the power unit is not equipped for automatic demagnetization, it may be accomplished as follows:

- Position the specimen in a coil, connected to DC or HWDC current.
- Adjust current control to a value at least as great as that which was used to magnetize the part.
- Give the coil a "shot" of current at that value.
- Reverse the direction of the current (use the current-reversing switch, if applicable; if not, reverse the cable leads connected to the output terminals), and reduce the current setting.
- Give the coil a "shot" of current at the new setting.
- Repeat the "reversing, reduction and shot" action in about 30 increments until the current setting is down to zero. (Commercial, stationary power units are frequently equipped with automatic 30-step switches for this purpose).

The foregoing demagnetization method works well for small parts in standard coils and for large parts with a full length cable-wrap coil. If an objectionable field still exists in large, hard parts, it is advisable to use the through-current technique whereby the magnetizing current is passed through the part with the "reversing, reduction and shot" method employed.

Yokes

Yokes are available that operate from variable DC current, but most yokes used for industrial applications are either the 110 VAC type or the permanent magnet type.

Yokes which are energized with AC can be put on and removed from a specimen in the unmagnetized condition, and can also be used for demagnetizing as well as magnetizing. The permanent magnet types produce a weaker flux field, and are, therefore, somewhat limited in range of applications.

Yokes are used in a manner similar to using prods. The magnetic field produced is weaker, however, and it is recommended that the continuous method of magnetization and particle application be used. Typical tests are conducted as follows:

- Position the yoke on the specimen over the area to be examined.
- Energize the yoke (if electric type) and apply the magnetic particles.
- Examine for discontinuities before removing yoke and again after removing the yoke.
- Re-position the yoke over the same area (rotating the yoke about 90°), and repeat the test.

Ultravoilet Inspection Lights

The ultraviolet or "black" lights used in magnetic particle inspection with fluorescent particles, usually consist of a ventilated housing, a mercury vapor arc lamp, and a suitable optical filter. The filter is designed to filter out harmful short waves of light, and pass a maximum amount of wave lengths which activate the fluorescent dyes in the inspection medium. The dyes typically fluoresce with a brilliant green-yellow color which is highly visible to the eye under normal subdued light inspection viewing conditions. Most portable, hand held "black" lights use a 100 watt "spot" mercury lamp. In stationary test set-ups, large 400 watt lamp units may be mounted permanently to the power unit.

The intensity of the black light at the point of inspection is a critical factor in a test, because the amount of visible light emitted from a fluorescent pigment is directly proportional to the amount of black light energy supplied to the test surface. For this reason, the lamps are checked frequently with a suitable light meter to verify that the light output has not diminished, and is adequate for use. Experience has shown that a black light intensity of 90 foot candles at the point of inspection is the minimum intensity suitable for locating fine indications, such as those resulting from grinding cracks or heat-treating cracks. Even at this intensity, it is assumed that most of the background light (room lighting, sunlight, etc.) has been excluded from the inspection area with the use of opaque curtains or a darkroom constructed for that purpose.

Following the magnetization of the test specimen and application of the fluorescent magnetic particles, the inspector proceeds with the examination for discontinuities with the black light as follows:

- Turn the current on the lamp, if not previously done, and allow a minimum of 5 minutes warm-up time (to allow the arc to stabilize and reach maximum intensity).
- Hold the lamp approximately 15 inches from the test surface, with the beam focused on the area under examination. The lamp should be held at such an angle from the surface of the specimen that reflection of the light into the eyes does not occur.

- Leave the lamp on during the entire test or working period; switching on and off shortens the life of the lamp.
- Observe for indication of discontinuities.

DETECTABLE DISCONTINUITIES

The basic function of magnetic particle testing is to identify the presence of discontinuities. The detection of any discontinuity is dependent on the sensitivity of the specific technique of magnetizing and applying particles, as related to the size, shape, orientation and location of the discontinuity. The only classifications of discontinuities that are meaningful in this regard are: (1) those discontinuities that constitute a break in the surface of the part (open to the surface), and (2) those which lie wholly below the surface (within the part.)

Surface Discontinuities

Surface discontinuities represent the largest group and those easiest to locate with magnetic particle testing. Surface discontinuities may seriously affect the service life of the part, and include such defects as fatigue and service cracks, seams, laps, quenching and grinding cracks, and shrinkage cracks which occur on the surfaces of castings, forgings and weldments. In most cases, such discontinuities are detected easily due to the strong and highly localized leakage fields which occur. The most favorable characteristics of a surface discontinuity for its detection are:

- depth of discontinuity approximately at right angles to surface

- width at surface is small with a minimum air gap
- length at surface is large with respect to its width
- depth approximately 5 times as deep as its opening at the surface

The relationship between the surface opening and the depth of the discontinuity has a significant effect on detectability. Surface scratches may be as wide at the surface as they are deep, and usually will not form a magnetic particle pattern. Fatigue cracks and fine grinding cracks may have depths less than 0.001", but because the surface opening are 1/10 of that value or less, they are readily detectable using the wet method. These two examples, illustrate the importance of surface opening to depth ratio for capability of detecting surface discontinuities.

Subsurface Discontinuities

Discontinuities lying wholly below the surface present a more difficult problem for detection. With respect to the serviceability of the part, however, whether such discontinuities represent serious defects or not depends on the nature of the discontinuity. Subsurface discontinuities may be small voids or non-metallic inclusions which lie near to the surface, and are present to some extent in all steel products. Such discontinuities produce weak leakage fields, and can only be found when located very close to the surface.

A more serious type of subsurface discontinuity may occur deep in heavy sections, in the form of subsurface lack of fusion or lack of penetration in welds; cracks in weld passes; or internal shrinks, slag inclusions or gas pockets in castings. Detection of such discontinuities depends on a strong flux field emerging at the surface of the specimen as a result of magnetic field distortion by the discontinuity. This is illustrated in Figure 32-4-2. The "spread" of the emergent field increases with the depth of the discontinuity. As the "spread" increases, the emergent field becomes weaker until the magnetic particles are not attracted, and no indication appears. The size, shape and orientation of the discontinuity have a significant effect on the emergent field which is generated, but the depth (amount of metal between the discontinuity and the surface) is the dominant factor.

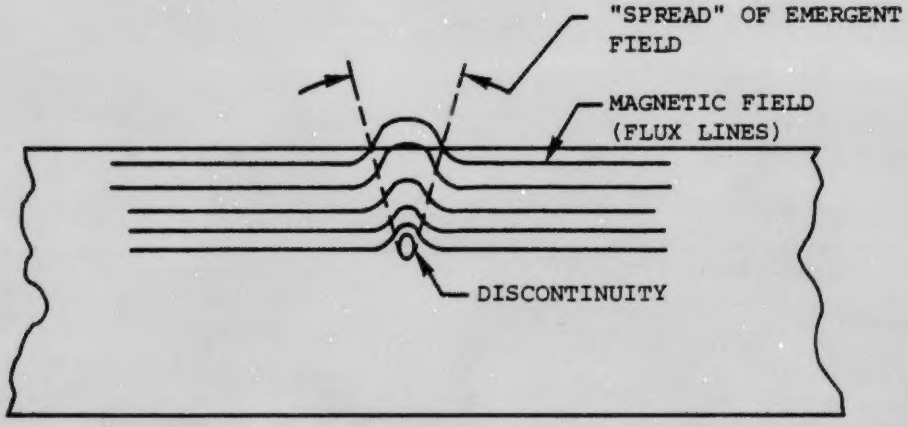


Figure 32-4-2 Spread of Emergent Field at a Discontinuity

In testing for deep-lying discontinuities, greatest test sensitivity can be obtained with the use of HWDC current magnetization and dry powder inspection medium. The "overall" method of magnetization (magnetizing entire specimen with high amperage current) produces optimum results for such tests, with the "prod" method and dry powder being the second choice.

A high degree of operator skill, however, even with an ideal test arrangement and procedure, is essential for success. The powder must be applied as a light, even, dust cloud, and observed carefully as it settles onto the part. Faint patterns, indicating leakage fields, may be formed as the first particles reach the surface, only to be obscured by additional particle accumulation. Excess particles must be blown very gently and carefully from the surface to re-establish a visible pattern. Even with great care exercised, the leakage field may be so weak that the particles indicating the pattern are also blown away.

NON-RELEVANT INDICATIONS

Definition

Indications which are formed by magnetic leakage fields but are not attributed to discontinuities or conditions that are relevant to the strength or useability of the part are considered non-relevant indications. Some of the common types of non-relevant indications are (1) external poles, (2) all-over patterns, (3) magnetic writing, (4) constructions, (5) cold working (6) dissimular metals, and (7) non-magnetic junctions.

External Poles

External magnetic poles may be created on parts at sharp corners, edges and ridges, and surface irregularities. Such poles are most likely to occur when longitudinal magnetization is used, and particularly when an excessive magnetizing force is applied. If the inspector has difficulty evaluating such indications, the part should be demagnetized, remagnetized at a lower level or in a different direction, and reinspected.

All-Over Patterns

When prods are used with an excessive magnetizing current to produce circular magnetic field in a part, indications of flux lines of the external field may be produced. This can be avoided by magnetizing at a lower power level. If the condition is extreme, it may be necessary to demagnetize the part, and then remagnetize at a lower level and reinspect.

Magnetic Writing

When parts come into contact with each other when either or both is in a magnetized condition, but not in the same degree, local poles may be formed at the areas of contact. One part may rub against the other in a random linear pattern. These magnetized "lines" attract magnetic partlces and resemble a fuzzy scrawl. The condition can be avoided by preventing parts from coming into contact with other magnetized parts. To eliminate "magnetic writing" from a part, the part needs only to be de-magnetized. The inspector may wish to then remagnetize the part and reinspect to verify that the condition was a non-relevant indication.

Constriction in Metal Path

Parts whose inside or back surfaces (relative to the surface inspected) are contoured, stepped, or otherwise sharply shaped differently from the surface inspected may show unwanted indications or outlines of these inside or back shapes when inspected, particularly when using circular magnetization. This may occur at the locations of internal gear teeth or splines or other characteristic areas where the magnetic flux lines are forced to the surface of the part because of constrictions or obstructions in the flux path. An experienced operator can easily relate such non-relevant indications to some cross-sectional or construction feature which accounts for the flux leakage-field. If the indication cannot be explained satisfactorily, the part should be demagnetized, and remagnetized and inspected at lower field strengths until the suspected non-relevant indications disappear.

Cold Working

Parts subjected to plastic deformation during cold working operations may exhibit nonrelevant indications when magnetic particle tested. These indications result from leakage fields caused by changes in grain structure and permeability in the parts. Cold working indications can usually be removed from a part only by heating the part above the curie point (transformation point at which a material becomes non-magnetic). The curie points for some ferromagnetic materials are listed in Table 32-4-5.

Table 32-4-5 Curie Points for Ferromagnetic Materials

Material	Curie Point, °C
Iron, 4% Maganese	715
Iron, 5% Silicon	720
Iron, 10% Chromium	740
Iron	770
Iron, 6% Vanadium	815

Welded Joints between Dissimilar Magnetic Materials

Steel materials which are different in hardness are also different in permeability. When any such dissimilar magnetic materials are joined by welding a magnetic leakage field will be concentrated at that point where the permeability of the materials changes sharply. Magnetic particles will produce a nonrelevant indication along the junction lines, but do not provide any information about the soundness of the joint.

Brazed Joints

The brazing of the ferromagnetic materials consists of fusing the joints together with a film of brass. Since the brass materials is non-magnetic, a magnetic discontinuity is formed at the joint. When the area is magnetic particle examined, the joint is outlined with particles even though the joint is structurally sound.

DETECTION, INTERPRETATION AND EVALUATION OF DISCONTINUITIES

Types of Discontinuities

It is important that each specimen that is to be examined be considered as a unique part, and the test applied to produce the required sensitivity. The technician must consider the origin of the part, whether it has been in service, and the type of service and length of time to which it has been exposed. The origin of the part determines the type of discontinuities which may be expected.

Inherent discontinuities and processing discontinuities should be expected to occur for parts not yet in service. Inherent discontinuities are discontinuities related to the solidification of molten metal in wrought and cast metal products, and include gas porosity, shrinkage cracks, inclusions, and internal fissures. Processing discontinuities are those resulting from any of the various metal working processes such as machinery, welding, forming, rolling, heat treating, and plating.

Typical discontinuities which result from processing operations include seams, laminations, cooling cracks (hot-rolled products), forging bursts, and various types of discontinuities in weldments.

If the part has been in service for a period of time service discontinuities in the form of cracks may be expected. These include fatigue cracks and stress corrosion cracks.

Gas Porosity

Gas porosity may be trapped in cooled metal in a cast product, a weldment, or in the original ingot. Porosity is usually rounded or elongated in shape, and may be either scattered throughout the metal or isolated in small groups or clusters. Porosity may be entirely subsurface, or open to the surface. Magnetic particle examination may be used to detect porosity open to the surface, but subsurface porosity does not produce a clearly defined pattern suitable for reliable detection and evaluation. Preferrable examination for subsurface porosity is radiography.

Shrinkage Cracks

Shrinkage cracks, open to the surface, may result from rapid or uneven cooling of cast or welded metal. Such cracks may range from very small, shallow, and tight, to open and deep. When examining for such discontinuities, it is important to induce the magnetic field in at least two different directions. If small, tight discontinuities are present, they may not produce indications if they are oriented parallel to the magnetic field.

Inclusions

Inclusions may be metallic or nonmetallic, and be found in any shape and surface or subsurface. Metallic inclusions are particles of metals of a different density as compared to the base metal. In weld metal tungsten inclusions may be found where the tungsten-inert-gas welding process (TIG) was used. Non-metallic inclusions are oxides, sulphides, slag or other non-metallic foreign matter trapped in a weld or in cast or ingot metal.

Magnetic particle examination is useful only for detecting inclusions at or very near the surface. Indications of such discontinuities may appear jagged, irregularly shaped and not well pronounced. A preferable method for detecting inclusions is radiographic.

Internal Fissures

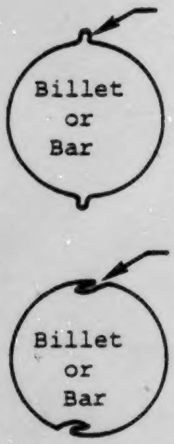
Internal fissures or voids may occur in ingots or casts as a result of shrinkage during cooling. When these occur in ingots, subsequent operations such as rolling may squeeze the sides of the void together and either fuse or weld the surfaces together (thereby eliminating the discontinuity, or create a "lamination" in the rolled product. Internal fissures usually cannot be detected with magnetic particle examination unless the void is very near to the surface examined. Radiographic examination is preferable for detecting internal fissures.

Laminations

Laminations are flat, planar discontinuities found in rolled plate or strip which are formed when internal voids are enlarged and flattened during the rolling operation. Such discontinuities are internal and lie in a plane parallel to the surface. Unless the lamination runs out to the edge of the plate, or the lamination is exposed at the end of a cut plate, it usually cannot be detected by magnetic particle examination. When the discontinuity is exposed on an edge, however, magnetic particle examination of that area will readily detect the defect, and produce a sharp, clearly defined linear indication. Ultrasonic examination is the most reliable method for internal laminations, as they present a planar, reflecting surface.

Laps

Laps are linear discontinuities that extend to the surface of rolled bars and forgings. They have the appearance of tight, longitudinal cracks. Laps may occur during the rolling process, such as during the rolling of ingots into billets, as the result of over-filling of the rolls. The production of a typical lap is illustrated in Figure 32-4-3. Laps may be severe, may run the entire length of the billet, and may render the billet useless for some products. Laps are easily detected with magnetic particle examination, and produce sharp, distinct linear indications.



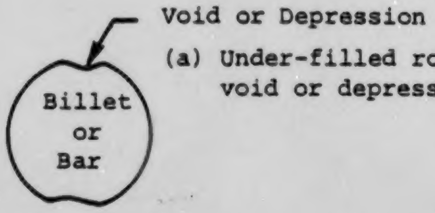
(a) Over-filled rolls squeeze-out excess metal as shown.

(b) Subsequent pass through the forming rolls squeezes the excess metal into an overlapping configuration as shown.

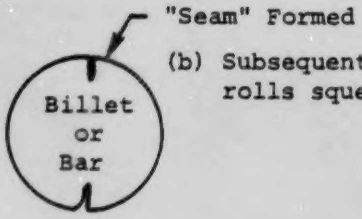
Figure 32-4-3 Production of Typical Lap

Seams

Seams are linear discontinuities that extend to the surface of rolled bars, and are formed in a manner similar to the formation of laps. Whereas laps are formed from over-filled rolls, seams are formed from under-filled rolls, as shown in Figure 32-4-4. Seams are usually crack-like discontinuities oriented nearly normal to the surface of the bar, and can easily be detected with magnetic particle examination.



(a) Under-filled rolls leave a longitudinal void or depression in the billet as shown.



(b) Subsequent pass through the forming rolls squeezes the void closed as shown.

Figure 32-4-4 Production of Typical Seam

Cooling Cracks

Cooling cracks are stress cracks that may occur in alloy steel bars due to the uneven cooling following roll-forming operations. Cooling cracks are usually longitudinal, variable in depth, and may be irregularly shaped rather than straight. Cooling cracks are easily detected with magnetic particle examination with the indications being stronger and more pronounced at locations where the crack is deepest.

Bursts

Bursts are irregular, internal cavities which may extend to the surface, that are found in wrought material which was forged, rolled, or extended. Bursts may result from forging material at too low a temperature, or from excessive working of the material during processing operations. Bursts may be large cavities, and are seldom healed or fused together during subsequent processing operations. Magnetic particle examination is only suitable for locating bursts at or near the surface of the part. Ultrasonic testing is usually used in examining for internal bursts.

Fatigue Cracks

Fatigue cracks are discontinuities which may occur in areas of stress concentration, such as fillets, splines, keyways, threads, oil holes, or holes for fasteners. Fatigue cracks usually begin as submicroscopic fissures and spread as a result of repeated stressing. Once started, a crack may progress quickly due to the increased stress concentration resulting from the crack itself. Fatigue cracks may ultimately lead to the failure of the part and are usually considered cause for rejection. Fatigue cracks are easily detected with magnetic particle examination, and from their, distinct hair-line indications.

Stress Corrosion Cracks

Parts which are exposed to a corrosive environment while under sustained tension in service may develop surface cracks known as stress corrosion cracks. This phenomena is more likely to occur faster at high levels of stress than at low levels, and may progress through the section until failure occurs. Although magnetic particle examination may be used quite satisfactorily to detect stress corrosion cracks in ferrous materials, liquid penetrant is commonly used since this type of defect occurs in both ferrous and nonferrous materials.

Discontinuities in Welds

Magnetic particle examination is used extensively to detect surface or near-surface discontinuities in welds. The discontinuities found produce indications similar to those described above for similar types of discontinuities in other types of ferromagnetic materials. The discontinuities in welds include:

- porosity
- lack of fusion (produces indication similar to that of a crack)
- shrinkage cracks (from improper cooling or heat control)
- non-metallic inclusions, or metallic inclusions of a density different than that of the weld metal.

Discontinuities Introduced in Finishing Operations

Many times parts may be processed through manufacturing operations, free from all objectionable discontinuities, up to the point of finishing or final processing only to be damaged beyond repair during heat treating, grinding, machining, plating, pickling, or acid etching. The discontinuities produced are open to the surface, detectable with magnetic particle examination, and described as follows:

- Heat treating cracks - During the heating and cooling processes associated with heat treating, localized stresses may be induced by thermal imbalance. If the stresses exceed the tensile strength of the material, cracking occurs. Such cracking usually occurs in areas of rapid material thickness change such as around keyways, grooves, basses, fillets and webs. These cracks are usually deep and forced, irregular in shape, and arranged in random patterns.

- Grinding cracks - Grinding cracks are surface cracks which are caused by stresses setup by localized heating under the grinding wheel. Grinding cracks are very shallow and resemble heat treating cracks. They usually occur in groups, and at right angles to the direction of grinding. Grinding cracks can be avoided by using proper grinding wheel, coolant, and rate of feed.
- Machining - Machining tears result when an article is worked with a dull tool or when an excessively deep cut is made. Metal is actually torn from the surface, and numerous short, surface discontinuities are produced.
- Plating - Plating cracks sometimes result from the plating process when plating with hardened materials. Such cracks are very thin and tight, and require careful examination to detect them.
- Pickling or acid etching - Hardened surfaces which contain residual stresses may crack when exposed to acids in the pickling or etching processes. The acid attack on the surface fibers of the material appears to trigger the cracking/stress relief action, and produces fine, irregular cracks.

EXERCISES

1. Fill in the blanks in the following statements:
   a. Magnetic particles may be applied by the _______________ method or the _____________ method.
   b. The ______________ method is the method of applying the magnetic particles to the specimen with the magnetizing current turned off.
   c. The residual magnetization method can only be used effectively on specimens having _____________ retentivity.
   d. Greater sensitivity can usually be obtained by applying magnetic particles with the ____________ method.
   e. Maximum indications will be produced by discontinuities which lie _______________ to the magnetic lines of force.
   f. It is usually recommended that a specimen be magnetized in at least _______________ directions to provide adequate assurance of detecting possible discontinuities.

2. A longitudinal field is induced in a large test specimen by using a coil with 8 turns wrapped around the part. If a current of 800 amperes is passed through the coil, what magnetizing force is applied (in ampere-turns)?

3. A test specimen is a solid bar measuring 20" long and 4" in diameter.
   a. What is the L/D ratio of the specimen?
   b. Does the resulting L/D ratio indicate that the part is suitable for coil magnetism?
   c. Calculate the current required for magnetizing the speciment with a 5-turn coil.

4. In magnetizing a part using prods, what is the recommended current range using a prod spacing of 7 inches or ½" thick material?

5. What basic types of current output are usually available on portable, mobile, and stationary magnetic particle power units?

6. Stationary units are usually used with what method of magnetic particle application/inspection?

7. The settling test is used for what purpose?

8. What method of demagnetization is easiest to use?

9. What is the recommended minimum black light intensity at the point of inspection?

10. What physical phenomenon is required on the surface of a test specimen to detect a discontinuity with magnetic particle examination?

11. What is the most sensitive method for examining for deep-lying discontinuities by magnetic particle examination?
    current ________________
    inspection medium ________________

12. External poles, constrictions in metal path of test specimens, joints between dissimilar metals, and cold working operations may produce ________________ in parts examined.

13. Residual magnetism in a specimen may be removed by heating it to its ________________.

14. List the three basic classifications of discontinuities as related to their origin:
    a. ________________
    b. ________________
    c. ________________

MATERIALS

The following materials are required to support this module.

1. Portable or mobile power supply unit, with variable outputs for HWDC and AC current
2. Portable, electromagnetic yoke (110V AC types)
3. Portable, permanent magnet yoke
4. Black light inspection lamp

5. Inspection media:
    - Red and black dry powders
    - *Red wet-bath suspension powder and solvent
    - *Fluroescent wet-bath suspension powder and solvent
6. Demagnetizing coil (110V AC type)
7. Inspection media applicators
    - Dry powder squeeze bulb
    - Wet-bath hand sprayer
8. Light meter for checking black light lamp output
9. Magnetic field indicator
10. Test speciments with typical defects or discontinuities.

*These materials may be obtained pre-mixed and packaged in aerosal cans.

PROCEDURES

1. Obtain from the instructor a part to be inspected and prepare an inspection procedure for examining the part by magnetic particle testing. Include:
    a. Type and value of current
    b. Type of magnetizing apparatus
    c. Magnetizing method
    d. Type of particles
    e. Method of particle application
    f. Demagnetization method
2. Examine the part supplied for Procedure #1 using the developed procedure.

3. Examine the part supplied for Procedure #1 using different magnetizing methods and compare results with the original method.

DATA TABLE

None.

REFERENCE MATERIALS

Betz, C.E., Principles of Magnetic Particle Testing, Magnaflux Corporation, Chicago, Illinois.

Libby, Hugo L., Introduction to Electromagnetic Nondestructive Test Methods

McGonnagle, Warren J., Nondestructive Testing, New York, McCowan Hill Book Company

Metals Handbook, Volume 11, Nondestructive Inspection and Quality Control, American Society for Metals

Nondestructive Testing Handbook, edited by Robert C. McMaster, Ronald Press

TEST

1. Name two methods for applying magnetic particles and relate their relative sensitivities.

2. Relate the orientation between magnetic field and discontinuity with the ability to detect the discontinuity.

3. State the thumb rule for determining current values for magnetic particle examination by circular magnetization of bars with:
   a. Half wave direct current:

   b. Alternating current:

4. What L/D ratio range is best for longitudinal magnetization of small parts?

5. Calculate the current for longitudinal magnetizing a tubular product whose length is 15 inches and diameter is 3 inches using a 10 turn coil.

6. State the recommended range of spacing of prods used for magnetic particle examination.

7. State the rule of thumb for determining current for magnetic particle testing with prods.

8. Name three types of power units used in magnetic particle examinations.

9. Briefly describe the conduct of a dry powder magnetic particle examination of a flat surface using a portable unit and prods. Include setting of current, spacing of prods, orientation of prods, and application of particles.

10. Briefly describe the conduct of a wet fluorescent magnetic particle examinations of a valve stem using (a) head stocks and (b) coil. Include setting of currents, application of particles, and observation for indication.

a.

b.

11. State the purpose of a "settling test" with respect to magnetic particle examinations.

12. Relate the location of discontinuities with respect to material thickness and the ability of magnetic particle examination to detect the continuity.

13. What is more easily detected by magnetic particle examination: shallow, open surface discontinuities, or tight, deep surface discontinuities.

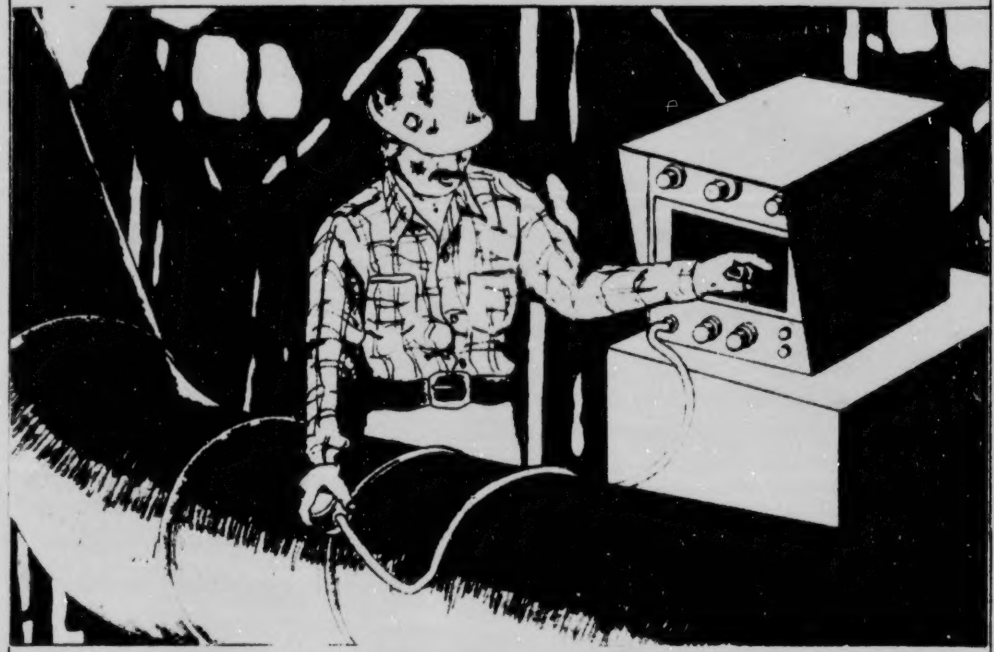
14. Describe the importance of knowing the origin of various types of discontinuities.

15. Name any four discontinuities, state their origin, and describe the relative ability of their detection by magnetic particle examination.

NUCLEAR TECHNOLOGY

MODULE 32 - 5

FUNDAMENTALS OF EDDY CURRENT TESTING



COURSE 32: NONDESTRUCTIVE EXAMINATION (NDE)

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

MODULE 32-1	Fundamentals of Ultrasonic Testing
MODULE 32-2	Operation of Ultrasonic Test Equipment
MODULE 32-3	Fundamentals of Magnetic Particle Testing
MODULE 32-4	Operation of Magnetic Particle Test Equipment
MODULE 32-5	Fundamentals of Eddy Current Testing
MODULE 32-6	Operation of Eddy Current Test Equipment

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INTRODUCTION

The nuclear QA/QC technician can have several responsibilities with respect to eddy current testing. The technician may qualify as an eddy current tester and perform product testing. Also, the technician may be responsible for monitoring or auditing eddy current testing performed by others.

Eddy current testing involves complex relationships between a variety of material properties and the effects of such properties on the electrical characteristics of a test coil. In any given test application, the relationship of specific material properties are established to permit measurement of those properties of interest. Even so, other material properties influence the test to some degree.

This module describes the fundamental concepts applicable to eddy current testing in general. It presents the electrical concepts, material properties and their effects, types of eddy current test coils, and principles of operation of eddy current testing systems.

MODULE PREREQUISITES

The student shall have completed all previous modules of Course 32.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Define permeability, conductivity, magnetic flux density, inductance, and inductive reactance.
2. Relate the number and spacing of turns of a coil to the inductance or inductive reactance of the coil.

3. Recognize voltage plane and impedance plane graphs of a coil and describe the effects on coil voltage and phase angle as inductance of the coil changes.
4. Describe the generation of eddy currents.
5. Describe the effects on eddy current by (a) magnetic field strength, (b) test frequency, (c) conductivity of the test piece, and (d) permeability of the test piece.
6. Name at least five factors which affect conductivity of a metallic alloy.
7. Describe why eddy current testing of magnetic alloys must be performed with the alloy magnetically saturated.
8. Describe lift-off effects.
9. Describe fill factor effects.
10. Describe fall off effects.
11. Describe end effects.
12. Describe the physical arrangements of surface coils, including gap coils and spring loaded coils.
13. Describe the physical arrangements of encircling coils.
14. Describe the physical arrangements of inside coils.
15. Describe an absolute coil.
16. Describe the use of differential coils in the self-comparison technique and the external comparison technique.
17. Describe the impedance analysis method of eddy current testing.
18. Describe how phase analysis circuits can distinguish between the conductivity variable and the dimension variable.
19. Describe the vector point method of phase analysis.
20. Describe the ellipse method of phase analysis.
21. Describe the linear time base method of phase analysis.
22. Describe modulation analysis.

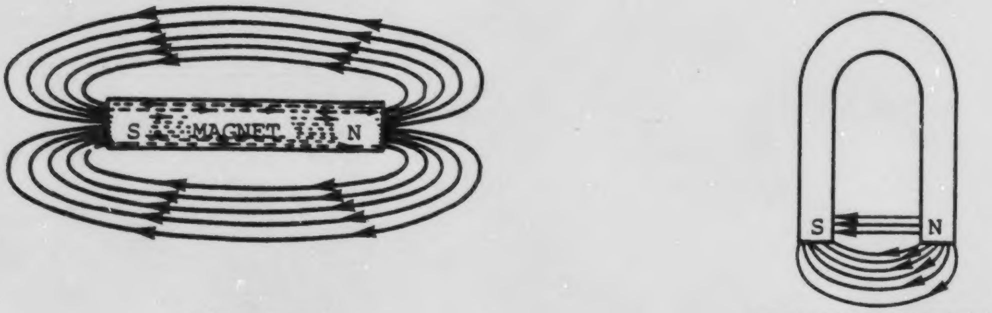
MAGNETIC PRINCIPLES

General

Eddy current testing uses the effect of the test piece on the inductive reactance of a test coil to determine properties of the test piece. It is necessary to understand inductive reactance, properties of materials which affect it, and the nature of the effects. Because all properties of materials which affect inductive reactance may be present in a given test piece, the nature of the effects of each property must be known if the test is to be used to detect only certain of these properties.

Magnetic Flux Density

We are familiar with common behavior of magnets. They attract certain materials (those which are magnetic) and do not attract other materials (those which are nonmagnetic). When two magnets are brought together, they attract in one orientation and repel when oppositely oriented. These behaviors of attraction and repulsion are due to magnetic lines of force which are present although invisible. Such magnetic lines of force are illustrated in Figure 32-5-1 for a bar magnet and a horseshoe magnet. The total number of magnetic lines of force is the magnetic flux. Because the term magnetic flux encompasses the entire field of lines of force, the term magnetic field is commonly used when speaking of the entire space within which flux exists. The number of magnetic lines of force per unit cross-sectional area is the magnetic flux density or, more simply, flux density. Thus, flux density increases as the number of magnetic lines of force increase within a given cross-sectional area. Likewise, flux density increases if somehow a given number of magnetic lines of force are squeezed into a smaller cross-sectional area.



BAR MAGNET HORSESHOE MAGNET

Figure 32-5-1. Magnetic Lines of Force

In 1819, Hans Christian Oersted, a Danish physicist, discovered that a definite relationship exists between electric current and magnetism. This relationship exists because electric current flow (current) generates magnetic lines of force. This flux is always at right angles to the direction of current. The direction of magnetic force (polarity) is dependent on the direction of current. Figure 32-5-2 illustrates these principles which can be determined for a straight conductor by applying the "right hand rule". By placing the right hand with the thumb in the direction of current, the fingers point in the direction of magnetic lines of force. It is noted that the lines of force are concentric to the longitudinal axis of the straight conductor.

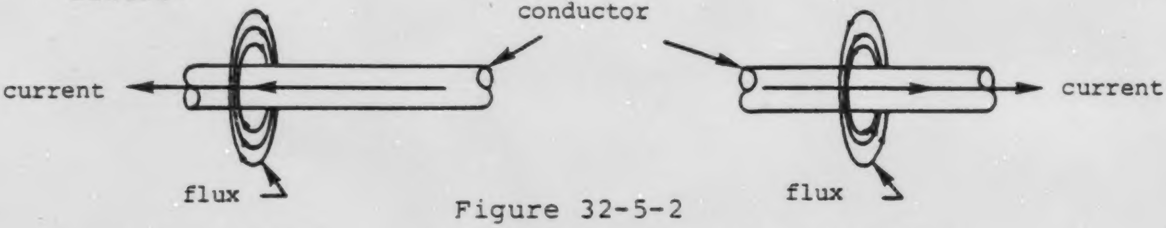


Figure 32-5-2

Magnetic Lines of Force in a Straight Conductor

If the straight conductor is formed into a circular loop, the magnetic lines of force at various cross-sectional areas around the loop combine such that the direction of the magnetic field is along the axis of the loop. As more circular loops are formed, this phenomenon produces a definite field pattern which is discerned by applying the "right hand rule". Referring to Figure 32-5-3, if the right hand is placed around the loop such that the fingers point in the direction of current, the thumb points toward the north pole of the magnetic field.

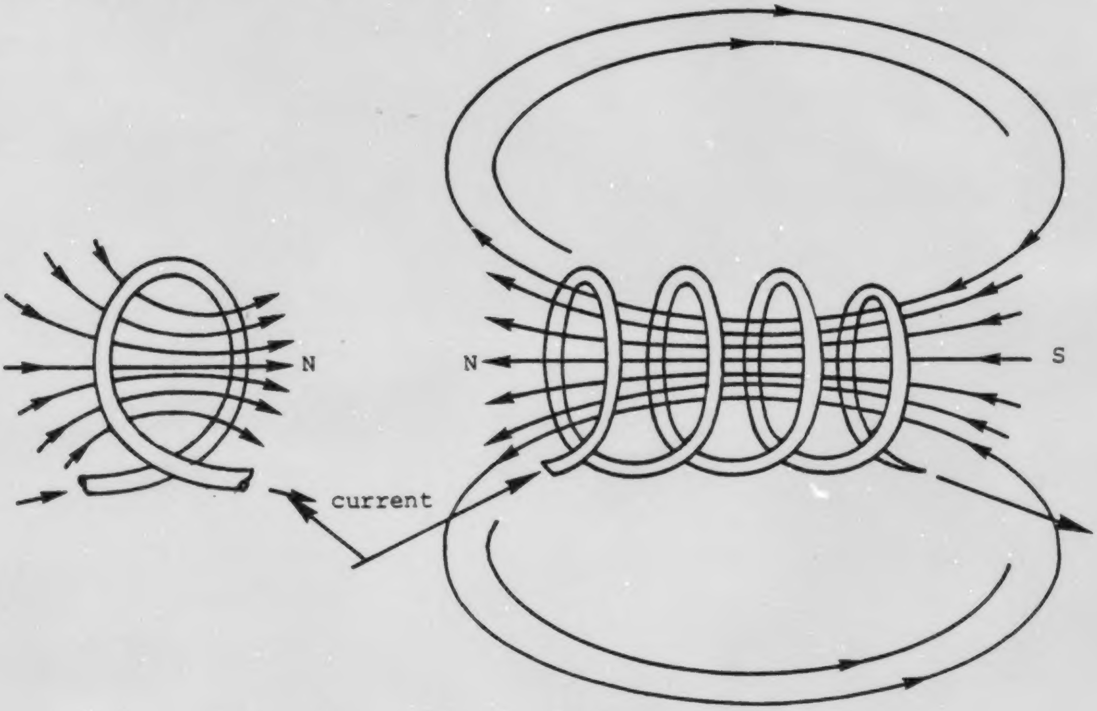


Figure 32-5-3. Flux in a Coil

The flux density at any given point within the magnetic field is a direct function of current. That is, as current increases, flux density increases. With constant current, flux density decreases with increasing distance from the coil. The decrease in flux density with distance is nonlinear. As explained later in this module, the decrease in flux density with distance affects the test depth of eddy current testing.

At a given distance from the coil and with constant current, flux density depends primarily upon the permeability of the material through which the flux exists. Permeability is a measure of the relative ability of a substance to conduct magnetic lines of force as compared with air. The permeability of air is arbitrarily assigned as 1. Permeability of all other substances is measured in relation to the permeability of air.

Permeability is represented by the Greek letter mu (μ) and is expressed by Equation 32-5-1.

$$\mu = \frac{B}{H} \qquad \text{Equation 32-5-1}$$

where

μ = permeability

B = flux density in gauss

H = intensity of magnetizing force in gilberts per centimeter of length

By rearranging Equation 32-5-1, the flux density is the product of permeability and magnetizing force: $B = \mu H$. Using this form of the equation, one can imagine what happens to flux density if a material with high permeability is inserted into the coil in Figure 32-5-3. Insertion of material of higher permeability into the coil increases the flux density with all other factors unchanged. As indicated by Equation 32-5-1, the effect of permeability on flux density is large. If permeability doubles, flux density doubles. A tripling of permeability triples flux density, and so on. This large effect of permeability has serious implications for eddy current testing as described later in this module.

Inductance

Inductance is the characteristic of an electrical circuit that makes itself evident by opposing the starting, stopping, or changing of current. Repeating the prior sentence in a more simplified form, inductance is the characteristic of an electrical circuit which opposes a change in current. Note that a change in current must occur for inductance to have effect. When the effect is present, it is always in opposition to the change in current. If current is increasing, inductance wants to prevent the increase. If current is decreasing, inductance wants to prevent the decrease.

An analogy of inductance is the mechanical movement of an object. Anyone who has pushed a car or a loaded wheelbarrow knows that it takes more work to start the object moving than it takes to keep it moving. This is because the object possesses inertia. Inertia is a characteristic of mass which opposes a change in velocity. Just as inertia opposes a change in velocity of a mechanical object, inductance opposes a change in current of an electrical circuit.

In 1831 in England, Michael Faraday performed experiments which demonstrated that current in one conductor is capable of inducing a voltage in another conductor. At the same time, Joseph Henry in New York discovered the property of self-induction of a coil. Work of these pioneers and later persons led to the development of electrical generators, induction motors, transformers, magnetic amplifiers, solenoids, relays, and other devices dependent upon induction.

Inductance is measured in units of the Henry. An inductor has an inductance of one henry if one volt is induced in the inductor when current through the inductor is changing at the rate of one ampere per second. The relationship of induced voltage, inductance, and rate of change of current is expressed by Equation 32-5-2.

$$E_{ind} = L\frac{\Delta I}{\Delta t} \qquad \text{Equation 32-5-2}$$

where

E_{ind} = induced electromotive force (emf) in volts

L = inductance in henrys

ΔI = change in current in amperes occurring in Δt seconds

Δt = time interval in seconds during which ΔI is determined

The process of induction can be envisioned as magnetic lines of force moving through a conductor and generating a voltage in the conductor by such movement. H.F.E. Lenz deduced that induced voltage is always a counter electromotive force (cemf). Lenz' Law states: "An induced emf always has such a direction as to oppose the action that produced it". Thus, a current varying in magnitude produces a varying magnetic field which sets up an induced emf that opposes the change in current producing it.

Inductance is largely dependent on magnetic coupling where magnetic coupling refers to the extent of the magnetic field passing through the inductor. A straight length wire has little magnetic coupling and therefore low inductance. The coil of Figure 32-5-3 has more magnetic coupling and a higher inductance. Coils with spaced loops have less coupling than coils with side-by-side loops. Double wound coils with overlapping loops have even greater coupling.

Magnetic coupling occurs whenever a conductor is located at any point within the magnetic field. If the conductor also carries the current which generates the magnetic field, as with a coil, self-coupling occurs and the resultant inductance is self-inductance. If the conductor does not carry the current which generates the magnetic field, the coupling is mutual coupling and a mutual inductance exists. An example of mutual inductance is the transformer illustrated in Figure 32-5-4 primary winding generates the magnetic field which is coupled to the secondary winding.

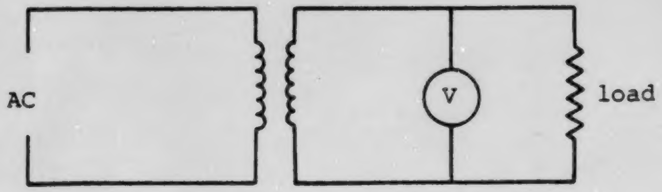


Figure 32-5-4. Transformer, Example of Mutual Inductance

Referring to Figure 32-5-4, the magnetic field of the primary winding induces a voltage in the secondary winding as measured by the voltmeter. The secondary voltage causes current flow through the load. One should note that current in the secondary winding also generates a magnetic field and this field is mutually coupled with the primary winding. In addition, each of the two windings has a self-coupling or self-inductance. Thus, there is self-inductance of each winding, mutual inductance from primary to secondary, and mutual inductance from secondary to primary. The interactions of such coupling are described later in this module using specific eddy current test probes.

Inductive Reactance

All materials offer some resistance to the flow of electric current through it. Good conductors, such as copper, silver, and aluminum, offer little resistance. Poor conductors, such as glass, wood, and paper, offer high resistance. The resistance of a material determines if we classify it as a conductor or an insulator. Resistance of a material is the same whether direct current without ripple or alternating current flows through the material. It is this resistance used in Ohm's law expressed by E = IR, where E is voltage in volts, I is amperage in amps, and R is resistance in ohms. As illustrated in Figure 32-5-5, current and voltage are in phase in a purely resistive AC circuit.

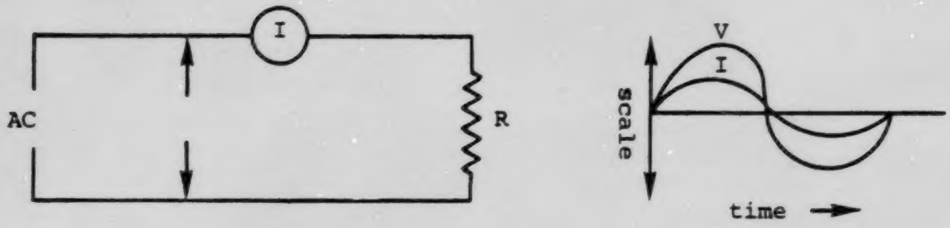


Figure 32-5-5. In Phase Current and Voltage

If the resistor of Figure 32-5-5 is replaced with a coil, opposition to current stems from two sources. One source is the resistance of the wires which form the coil and the circuit. This resistance is relatively small because a good conductor is used. The second source of opposition to current is the inductance of the coil. This opposition stems from the self-induced voltage which is a counter electromotive force (cemf) according to Lenz's law. This cemf opposes the applied emf and the AC power supply sees an opposition to current flow.

The opposition to current flow is measured in ohms as previously stated. Rather than speaking of cemf of the coil in volts, we need a term expressed in ohms for the inductor's opposition to current flow. The term is inductive reactance. Thus, inductive reactance is the opposition offered by a coil to alternating current. It is designated

X_L and expressed by Equation 32-5-3. As indicated by the equation, if either frequency or inductance changes, inductive reactance changes.

$$X_L = 2\pi fl \qquad \text{Equation 32-5-3}$$

where

X_L = inductive reactance in ohms
f = frequency in hertz
L = inductance in henrys

Inductive reactance causes current to lag voltage. Unlike a purely resistive AC circuit where current is in phase with voltage, a reactive circuit causes an out of phase relationship. In a theoretical purely reactive AC circuit, current lags voltage by 90° as illustrated in Figure 32-5-6.

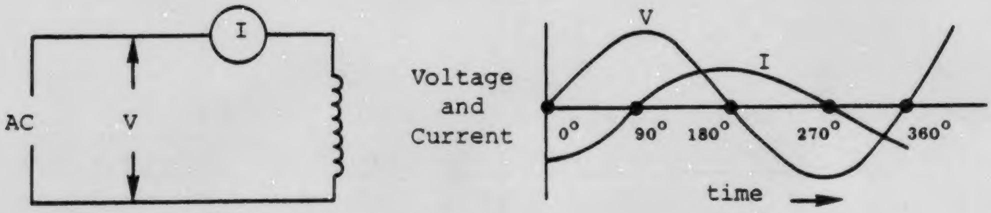


Figure 32-5-6. Purdy Inductive AC Circuit

In reality, inductive circuits have resistance if only from the resistance of the conductors which comprise the circuit. With respect to a coil, the windings of the coil have resistance and the coil has an inductive reactance. Thus, the coil can be diagramed as consisting of a pure inductor and a pure resistor in series where the value of the resistor is the resistance of the windings and the value of the inductor is the inductance of the coil.

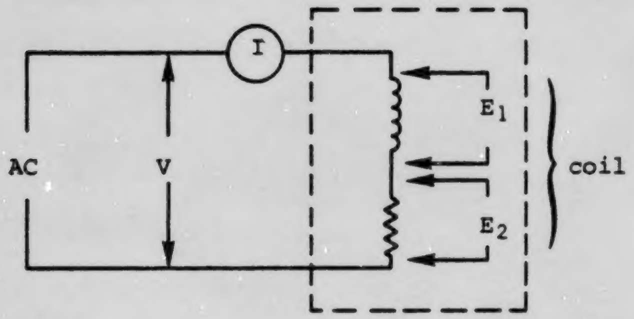
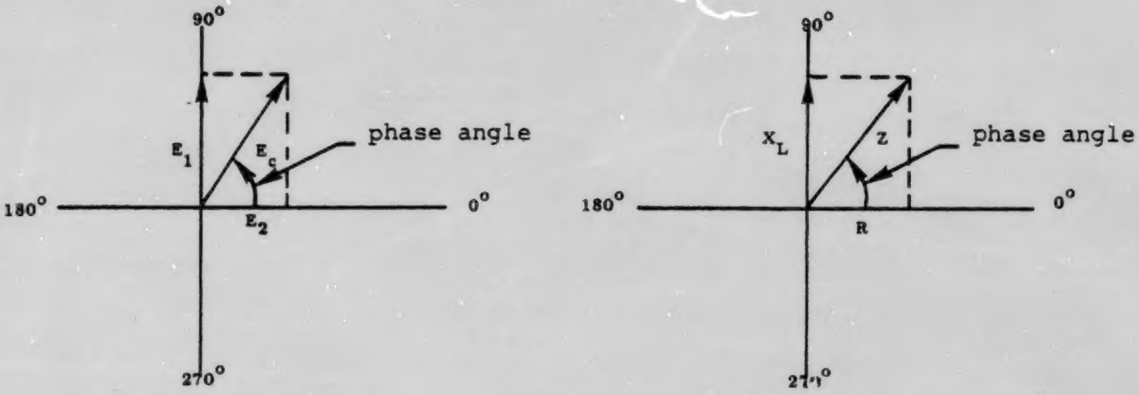


Figure 32-5-7. Schematic Diagram of Coil

Referring to Figure 32-5-7, it can be stated that current at any point in the circuit is the same at any instant of time. This is because there is only one current path in a series circuit. The voltages are designated as E, for voltage across the inductive component of the inductor and E_2 for voltage across the resistive component of the inductor. Using Ohm's law as the basis, E_1 must equal current times inductive reactance: $E_1 = IX_1$. Voltage across the resistor, E_2, must equal current times the resistance: $E_2 = IR$. However, current lags voltage in an inductive circuit. As illustrated in Figure 32-5-6, the current lags voltage by 90° in a purely reactive circuit. Thus, the E_1 voltage of Figure 32-5-7 must be ahead of the current; that is, E_1 leads the current. But E_2 must be in phase with the current as illustrated in Figure 32-5-5. Therefore, E_1 must be 90° ahead of E_2 or E_1 leads E_2 by 90°.

The relationship of E_1 and E_2 of Figure 32-5-7 is graphically plotted in Figure 32-5-8. This voltage plane graph identifies the phase relationship of E_1 and E_2 and represents the magnitude of these voltages by the length of the vectors. By vectorial addition of these two vectors, the actual voltage across the coil, Ec, is determined as well as its phase. The true opposition to current is found by dividing coil voltage, Ec by the current, I. Such opposition is comprised of inductive reactance and resistance and is termed impedance and symbolized as Z. An impedance plane graph plots the X_L and R vectors to determine the magnitude and phase of impedance.



Voltage Plane

Impedance Plane

Figure 32-5-8. Voltage and Impedance Planes of a Coil

By studying the voltage and impedance planes of Figure 32-5-8, one can observe that as the ratio of inductance to resistance increases, the phase angle increases. In other words, if the inductive reactance of the coil increases while its resistance is constant, the phase angle increases. Likewise, if the inductive reactance of the coil increases while its resistance is constant, the coil voltage increases. Similarly, decreases in inductive reactance with constant resistance result in decreased coil voltage and phase angle.

Eddy Current Generation

If a conductor is brought into the magnetic field of an AC coil, a voltage is induced in the conductor. This induced voltage provides the force for current flow. We know that current must have a path for flow. The load on the transformer in Figure 32-5-4 gives a path for current. But what happens if there is no path for current flow in the classical sense?

Referring to Figure 32-5-9, a metal is placed within the magnetic field of an AC coil. The metal has relatively low resistance. Since conductance is the opposite of resistance, the metal has a high conductance. Therefore, the metal is quite capable of supporting current flow but it does not offer a flow path in the classical sense. But, the metal offers a variety of flow paths within the metal itself. Consequently, current circulates within the metal. These circulating currents are termed eddy currents. Thus, eddy currents are induced currents which circulate within a conductor.

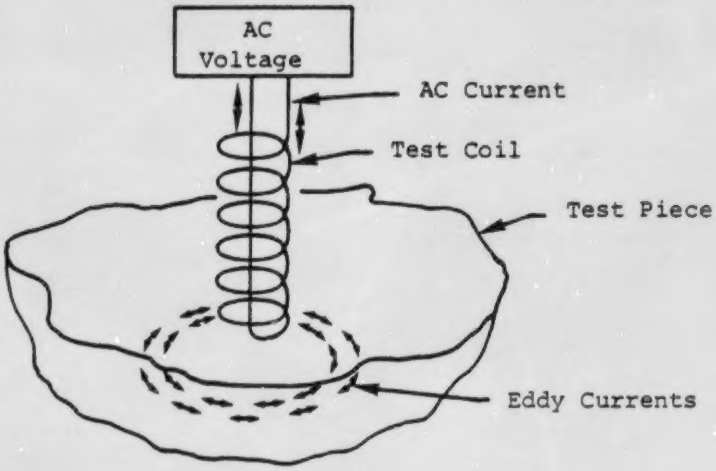


Figure 32-5-9. Eddy Currents

Eddy currents in a test piece generate their own magnetic field. The eddy current magnetic field is mutually coupled with the coil just as the coil's magnetic field is mutually coupled with the test piece. Thus, a number of variables affect the electrical characteristics of the circuits. In essence, anything that changes flux density within the magnetic field of the coil affects the self-inductance of the coil. Measurement of the coil's electrical properties permits correlation with those things which affect the coil. The major difficulty is in the ability to discern which of the many properties are affecting the coil.

EDDY CURRENT PRINCIPLES

Basic Test Process

Eddy current testing is a nondestructive test method which measures material properties through the reaction of such properties to the test coil. The basic test system is illustrated by the block diagram of Figure 32-5-10.

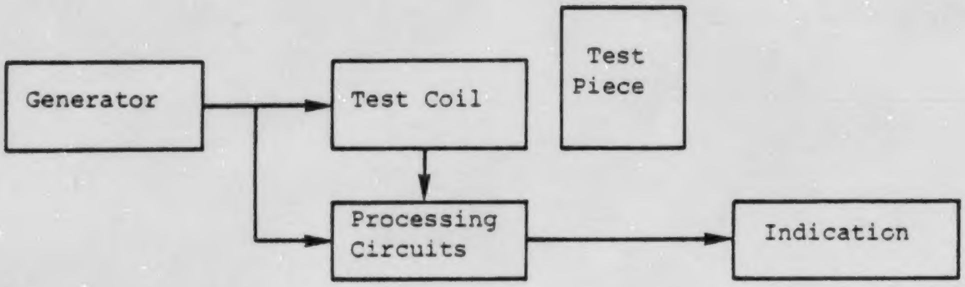


Figure 32-5-10. Basis Eddy Current Test System

Referring to Figure 32-2-10, the generator establishes an AC voltage at a desired frequency. The AC voltage is applied to the test coil and, in most applications, to the processing circuits to assist in making meaningful analysis of the electrical characteristics of the coil. The test coil induces eddy currents in the test piece. Properties of the coil and the test piece which affect magnetic coupling effect the inductive reactance of the coil. The processing circuits measure the coil's electrical characteristics and either compare them with a standard or determine if they change. The comparison or change is processed in such a way as to enable determination of those test piece properties causing the effect. The result is indicated by meter, cathode ray tube, or strip chart recorder. The essential variables of the test are the type of coil, the applied frequency, the test piece properties, and the proximity of the coil to the test piece. For a given test system, all these essential variables are fixed except for test piece properties and possibly the proximity of test coil to test piece.

Factors Affecting Eddy Current Testing

The factors which effect eddy current testing and thus affect the test indication are broadly categorized as (1) penetration, (2) conductivity, (3) permeability, and (4) dimensions. Within each of these categories there are several factors which affect test results. These are described in subsequent paragraphs. In addition to these four categories, the test coil design affects the test. Test coil design is described separately in a later section.

Factors Affecting Penetration

The depth within a test piece at which eddy currents are sustained is affected by (1) strength of test coil's magnetic field in the test piece, (2) frequency applied to the test coil, (3) conductivity of the test piece, and (4) permeability of the test piece.

The test coil's magnetic field in the test piece decreases in flux density with increasing distance into the test piece. This is mostly because the flux generated by eddy currents opposes the inducing flux (Lenz Law). For a given test coil magnetic field, the strength of that field seen by the test piece decreases with depth in the test piece as measured from the test coil. Likewise, changing the strength of the test coil's magnetic field changes the depth within the test piece where a given flux density exists. Therefore, as test coil field strength increases, depth of penetration increases.

Frequency affects the depth of penetration of the test piece due to "skin effect" which is common to all conductors. The magnetic field generated by current flow tends to force the flowing electrons toward the outer surface of the conductor. This effect increases as frequency increases. Therefore, the depth at which eddy currents exist is affected by frequency applied to the test coil. As frequency of the test coil increases, depth of penetration decreases.

Conductivity affects the magnitude of eddy currents which in turn affects depth of penetration. As conductivity increases, the magnitude of eddy currents increases which results in a larger magnetic field generated by the eddy currents. This larger field forces the circulating currents closer to the surface. Therefore, as conductivity of the test piece increases, depth of penetration decreases.

Permeability affects the flux density in the test piece supported by the test coil's magnetic field. As permeability increases, a larger flux density is permitted for a given test coil field strength. The larger flux density induces larger circulating currents whose own larger magnetic fields both force circulating current toward the surface and more greatly counter the test coil's magnetic field. Therefore, as permeability increases, depth of penetration decreases.

In summary, penetration is affected by coil field strength, test frequency, conductivity of the test piece, and permeability of the test piece. The effects are:

- As coil field strength increases, depth of penetration increases.
- As test frequency increases, depth of penetration decreases.
- As conductivity of the test piece increases, depth of penetration decreases.
- As permeability of the test piece increases, depth of penetration decreases.

Factors Affecting Conductivity of Test Piece

Conductivity is frequently expressed in terms of the International Amended Copper Standard (IACS). This highly pure copper standard is defined as having 100% conductivity. The conductivity of other materials is expressed as a percentage relative to this standard. For example, pure gold has an IACS conductivity of 73% and pure aluminum has 66%. Factors affecting conductivity include (1) chemical composition, (2) heat treatment condition, (3) cold working condition, (4) lattice defects, (5) temperature, and (6) flaws.

The chemical composition of a metal affects conductivity of that metal. Whether it is a pure element, such as pure aluminum, or an alloy, such as stainless steel, metals offer a definite conductivity which is dependent on the chemical constituents of the metal. Chemical constituency affects conductivity whether it is comprised of the desired alloying ingredients or undesired impurities. However, because other factors affect conductivity, a given metal's conductivity varies over a finite range due to the influence of other factors. Therefore, conductivity ranges of various metals can overlap. Nonetheless, a definite correlation exists between a metal's conductivity and its chemical composition. Conductivity of a few metals is indicated for illustration purposes in Figure 32-5-11.

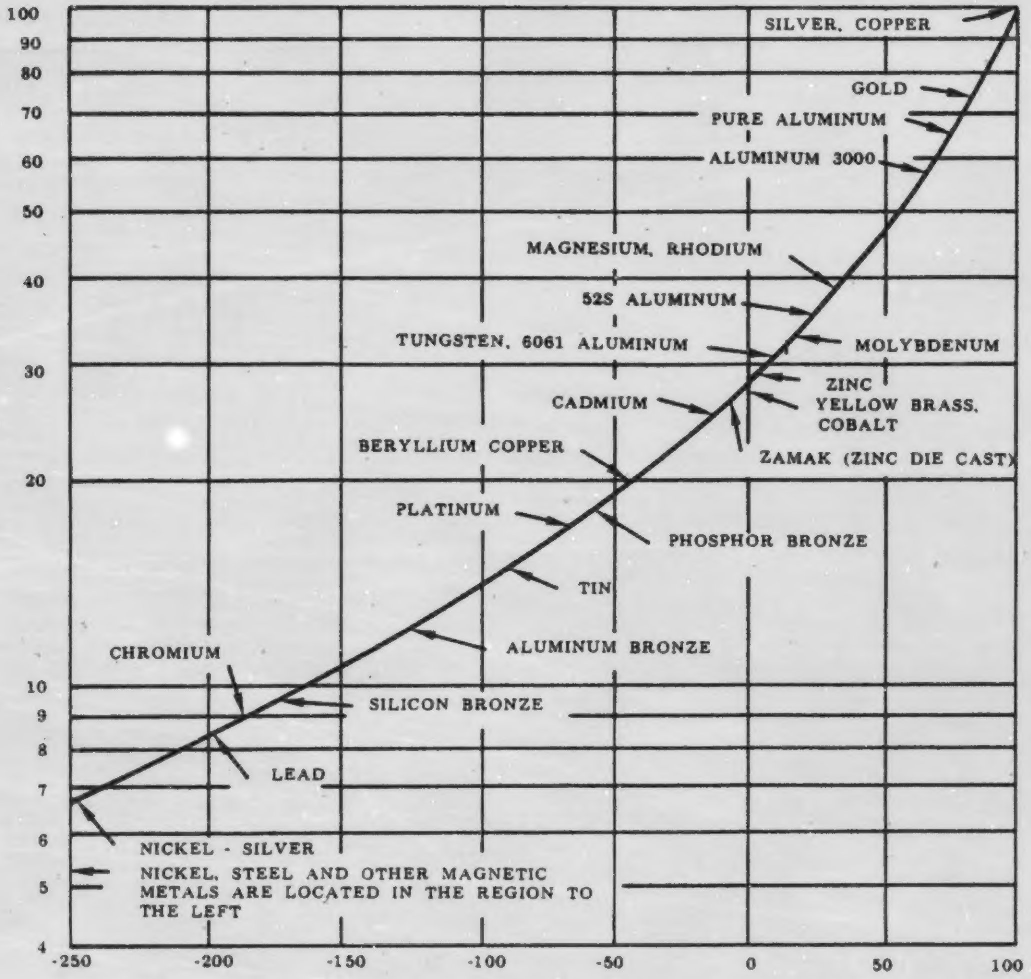


Figure 32-5-11. IACS Conductivity of Various Metals and Alloys Versus Eddy Current Readings

The heat treatment condition of metals and alloys determines the grain size, crystalline structure, and distribution of alloying ingredients and impurities within the grain pattern. All of these variables affect conductivity. In many cases, sufficient empirical data exist to permit determining the heat treatment condition by measuring conductivity.

Cold working of alloys distorts and disrupts crystalline lattices and grain boundaries. Such physical displacement affects the conductivity of the alloy.

Crystalline lattices can contain defects due to stressing, irradiation, and other causes. Such defects affect conductivity by altering the normal lattice structure.

For conductors, temperature inversely affects conductivity. That is, as temperature increases, conductivity decreases. In insulators there is an opposite effect. That is, as temperature increases, conductivity increases.

Flaws within the metal or alloy decrease conductivity in the area of the flaw. Any discontinuity in the crystalline structure is considered a flaw, such as porosity, inclusions, and cracks.

In summary, conductivity is affected by chemical constituency, heat treatment, cold working, lattice defects, temperature, and flaws. The exact effect is determined empirically through many experiments. Conductivity ranges of alloys sometimes overlap.

Factors Affecting Permeability of Test Piece

Values for permeability primarily depend upon (1) whether the alloy is magnetic and (2) for magnetic alloys, whether saturation occurs. Magnetic materials, such as iron and most iron alloys, have a relatively high permeability below saturation and low permeability above saturation. Because permeability is high and also nonlinear below saturation, permeability has the single largest effect on eddy currents within magnetic materials. For saturated magnetic materials and for non-magnetic conductors, permeability is relatively small and basically constant. Relative permeability of magnetic and non-magnetic alloys is illustrated in Figure 32-5-12.

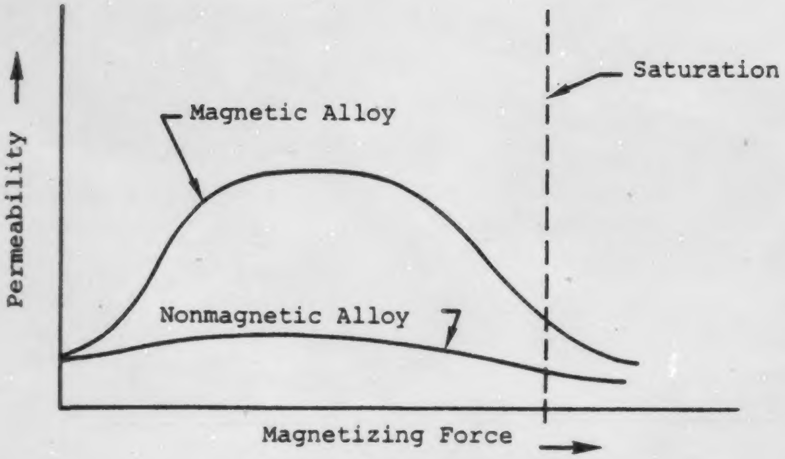


Figure 32-5-12. Relative Permeability of Magnetic and Non-magnetic Alloys

Review of Figure 32-5-12 reveals several important features with respect to eddy current testing. First, permeability can be considered relatively constant for non-magnetic materials regardless of the magnetic force. Second, permeability of magnetic alloys can be made relatively constant by saturating the alloy with an independent magnetizing force. In this manner, permeability would not vary with magnetizing force. Instead, internal stresses and lattice impurities would have the predominant effect on permeability. Thus, eddy current testing would be sensitive to internal stresses and lattice impurities.

Factors Affecting Dimensions

The dimensions associated with proximity of test coil to test piece, geometry of the coil, and geometry of the test piece are important with respect to eddy current testing. These dimensions affect the magnetic coupling between the coil and the test piece. As described previously in this module, changes in coupling change the magnitude of eddy currents. Dimensional effects are manifested as "lift-off", "fill factor", "fall-off" and "end effect".

Lift-off refers to the large change in output indication which occurs as a test coil is withdrawn from a conductive test piece. It is due to the decrease in flux density within the test piece as distance from the coil increases. The lift-off effect is so great that a change of 0.001 inch in test coil to test piece distance is measureable. This phenomenon offers advantages and disadvantages for eddy current testing. For tests of conductive materials, it is a disadvantage because of the need to maintain essentially constant spacing from test coil to test piece. It becomes an advantage in tests of non-conductive coatings, such as paints, on conductive materials. Dry film coating thickness measurements use the lift-off effect to determine coating thickness as illustrated in Figure 32-5-13.

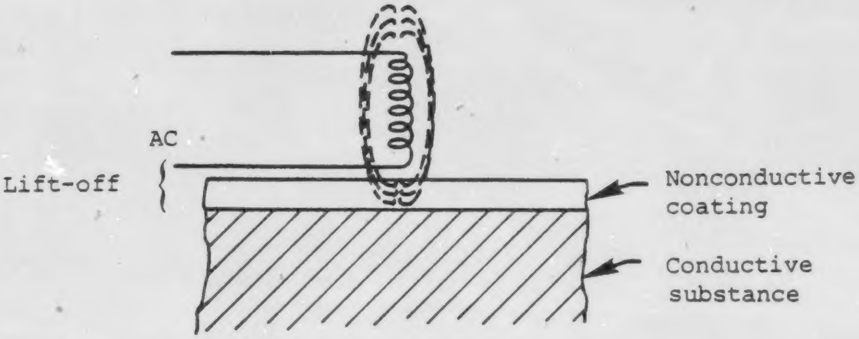


Figure 32-5-13. Lift-Off Effects Used for Coating Thickness Measurement

Fill factor is the equivalent of lift-off for encircling coils. As illustrated in Figure 32-5-14, fill factor expresses the extent to which circular product fills the volume within the encircling coil. Fill factor is expressed as$\left(\frac{D1}{D2}\right)^2$ and is always less than unity. A reduction in fill factor reduces sensitivity of eddy current testing. It is noted that a noncentering of the circular product within the coil affects fill factor.

Fall-off refers to the falling off of field strength at a distance from a test coil due to coil dimensions and shielding. The primary dimensions affecting fall-off are pole size and spacing. This is illustrated in Figure 32-5-14 for two pole sizes of equal spacing. The larger poles provide for greater penetration or less fall off.

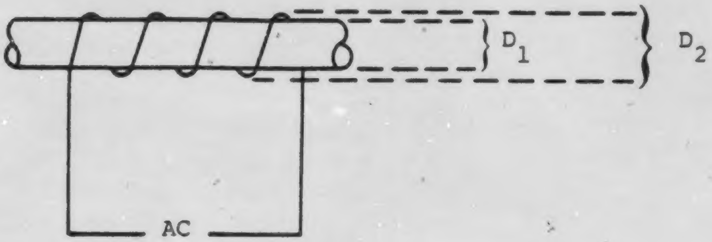


Figure 32-5-14. Fill Factor

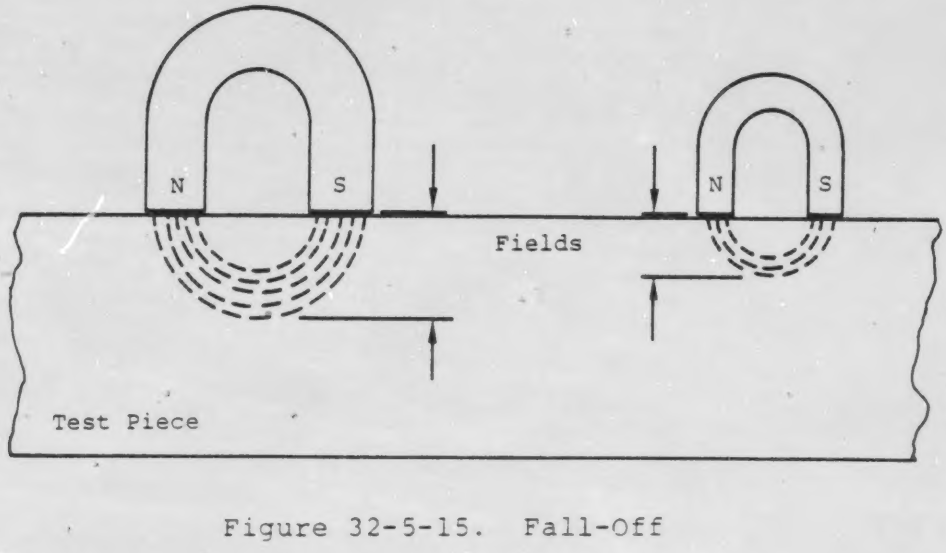


Figure 32-5-15. Fall-Off

Fall-off is also affected by the shielding within a coil. Shielding pinches or directs the field such that fall-off occurs rapidly with distance from the coil. An example of shielding is illustrated in Figure 32-5-16.

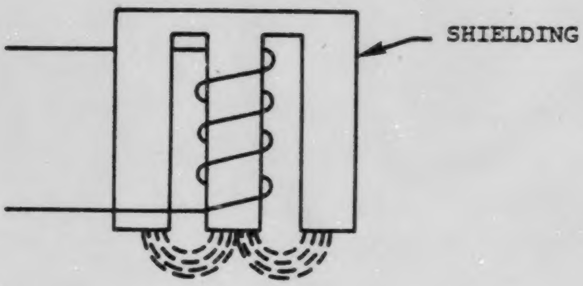


Figure 32-5-16. Shielding

End effect refers to the effect on eddy currents by an abrupt change in geometry of the test piece. Such abrupt changes are illustrated by edges, corners, holes, ends, etc. At such points, the coil's field is distorted by the test piece-to-air boundary. This reflects as an indication which can mask or obscure signals from material properties which are intended to be detected.

TEST COILS

General

The sensor for eddy current test systems is the test coil. Test coils are available in many arrangements and sizes in order to be adaptable to test piece size and configuration. Test coils may be single or double coils. Their arrangement can permit placement around, within, or on the test piece. Double coils include differential coils. Coils are wound on nonconductive material such as plastic although shielding may be used.

Surface Coils

Surface coils are designed for use on the surface of the test piece. Surface coils may be contacting or non-contacting and are shaped to match the contour of the test piece.

Surface coils are typically "gap" coils or spring-loaded coils. The gap coil uses magnetic shielding to confine the field to the gap between the shielding members. This is illustrated by Figure 32-5-16. Spring-loaded surface coils use spring pressure to maintain surface contact and, thereby, minimize lift-off effects. The spring loaded coil, which is illustrated by Figure 32-5-17, may be direct contacting or designed to hold the coil a fixed distance from the surface.

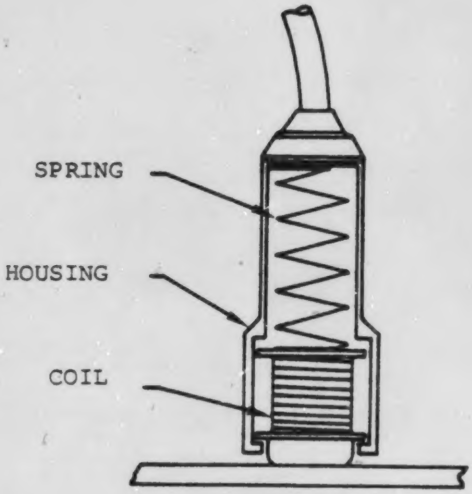


Figure 32-5-17. Spring-Loaded Surface Coil

Encircling Coils

Encircling coils encompass the test piece about an axis of the test piece. It is shaped similar to the shape of the test piece. That is, the encircling coil may be circular, squared, or rectangular. A circular encircling coil is illustrated in Figure 32-5-18.

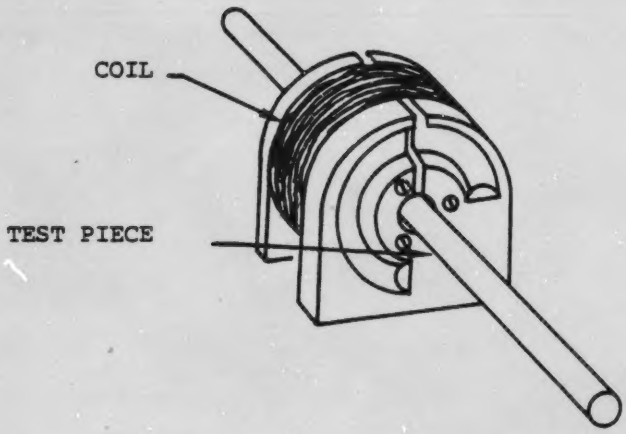


Figure 32-5-18. Encircling Coil-Circular

Inside Coils

Inside coils are arranged to permit insertion of the coil within the test piece. The most common application is for testing of tubing which requires a circular inside coil. Other shapes, however, are possible. Figure 32-5-19 illustrates an inside coil.

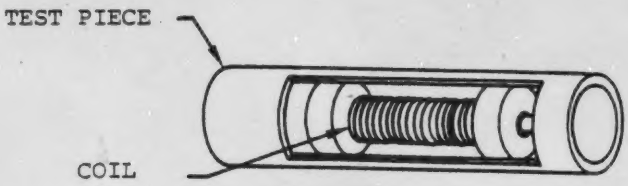


Figure 32-5-19. Inside Coil Circular

Absolute Coil

An absolute coil is one which tests the test piece without comparison to a standard. An absolute coil may be a contact coil, encircling coil, or inside coil. It may be single wound or double wound. It is termed absolute because it tests the material adjacent the coil without referencing the eddy current effect to anything else. Single and double absolute coils are illustrated in Figure 32-5-20.

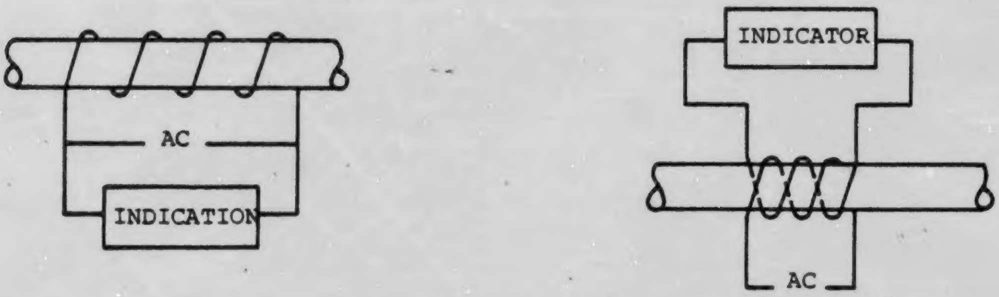
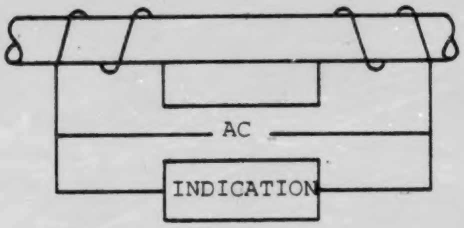


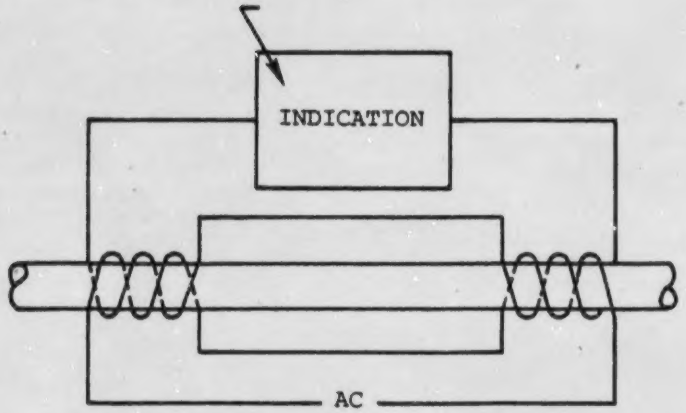
Figure 32-5-20. Absolute Coils

Self Comparison Technique

The self comparison technique uses differential coils to test two discrete areas of the test piece. If test piece properties are identical under each coil, the outputs of the two coils cancel. If a slight difference in properties exist under the coils, an output results. The differential coils may be single or double coils as illustrated in Figure 32-5-21.



Single Coils - Differentially Wound



Double Coils - Differentially Wound

Figure 32-5-21. Self Comparison Coils

External Comparison Technique

External comparison technique uses a reference standard for comparison with the test piece. Differential coils are used as in the self comparison technique but one coil measures the test piece and the other coil measures the reference standard. Differences in properties between the test piece and reference standard result in an output. Figure 32-5-22 illustrates the external comparison technique.

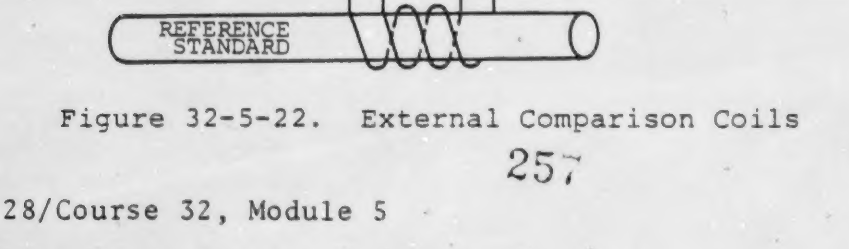


Figure 32-5-22. External Comparison Coils

PROCESSING CIRCUITS AND INDICATION

General

Figure 32-5-10 illustrates that processing circuits evaluate the effect of the test piece on the test coil and provide a meaningful indication (readout). Figure 32-5-8 pictures the measureable characteristics of the test coil as consisting of (1) impedance, (2) phase angle, and (3) combination of either voltage and phase angle or impedance and phase angle. Processing circuits measure these characteristics and translate the results into useful indication. Thus, processing circuits are classified as either impedance analysis or phase analysis. In addition, a specialized form of analysis exists which is termed modulation.

Impedance Analysis

Eddy current testing which employs impedance analysis is based on changes in the impedance of the test coil. Changes in impedance of the test coil changes current by the relationship of $I = \frac{E}{Z}$. The processing circuits convert the change in current to a meaningful indication. Impedance analysis is relatively simple and is used by many portable eddy current testers. Common applications include measurement of conductivity and tests for flaws.

Conductivity testing is used for (1) metal sorting, (2) hardness measurements, (3) heat treatment condition measurements, and (4) coating thickness measurements. Metal sorting consists of confirming or determining material identity by measuring its conductivity. As previously described, those materials which have overlapping conductivity ranges cannot be sorted with assurance by conductivity alone. Thus, conductivity testing often will not sort various grades of the same alloy.

But, for metals not having overlapping conductivity, eddy current testing using impedance analysis provides a quick means of determining the type of metal. Such a test is useful in detecting material mixups. Eddy current conductivity testing used for hardness measurements is based on decreases in conductivity as hardness increases. For specific alloys whose conductivity to hardness relationship has been well established, impedance testing can be calibrated to indicate hardness of the alloy. Similarly, where conductivity for each possible heat treatment condition of a given alloy has been well established, eddy current testing can verify which heat treatment condition exists. This is based on the change in conductivity with changes in metallurgical conditions of the alloy which are established by the heat treatment. For example, an alloy, whose hot worked conductivity is 72% IACS and whose hot worked and quenched conductivity is 53% IACS, can be sorted by heat treatment condition by impedance testing.

Impedance testing of coating thickness uses conductivity effects for conductive coatings and lift-off effects for nonconductive coatings. For conductive coatings, such as chrome plating, the frequency is set to give penetration just beyond the expected coating thickness. As actual coating thickness varies, conductivity seen by the test coil varies and, thus, the readout is proportional to coating thickness. As previously described, nonconductive coating thickness is measured by changes in output indication caused by variations in lift-off. For such measurements, the substrate must be conductive.

Impedance testing for flaws is a gross testing system which detects changes in the coil's impedance. Due to other factors which affect the coil's impedance, it is difficult to detect minute flaws. In such tests, it is important to minimize the influence of controllable factors such as frequency and lift-off or fill factor variations. Also, it must be recognized that penetration depth is limited and flaws deeper than the penetration depth are not detected. Impedance flaw detection is based on the disruption of eddy current paths caused by the flaw and the corresponding reaction on the coil's impedance. Minute flaws can produce such minor changes as to be indistinguishable from changes in other material properties which affect the test coil.

Phase Analysis

Phase analysis is more complex than impedance testing but has the capability of separating the conductivity variable from the permeability and dimension variables. As described later, permeability and dimension variables are inseparable. Phase analysis circuits typically evaluate the combination of either voltage and phase angle or impedance and phase angle. It uses differential coils arranged for either self comparison or external comparison. The indication represents the phase change and voltage or impedance change between the differential coils.

Referring to Figure 32-5-22, the output of the coils are equal provided the properties of the test piece are identical to those of the reference standard. With this condition, the indication is zero due to the differential arrangement of the coils. The question becomes what happens to the output as conductivity, permeability, and dimensions of the test piece change with respect to the reference standard.

If all factors of a number of test pieces are held constant except that each test piece has the different conductivity, the composite plot illustrated in Figure 32-5-23 is obtained. This plot connects the ends of the composite voltage vectors for each conductivity value of various test pieces. That is, it connects the voltage plane Ec vectors illustrated in Figure 32-5-8. Increasing conductivity causes the plot to move from A to B in Figure 32-5-23.

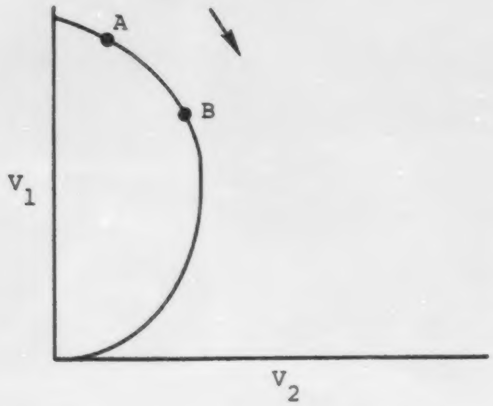


Figure 32-5-23. Ec Curve with Conductivity Changes

If conductivity of the test pieces is held constant and either dimensions or permeability are permitted to vary, a plot similar to that in Figure 32-5-24 is obtained. In this case, changes in either dimensions or permeability yield the same results. That is, an increase in either moves the plot from C to D.

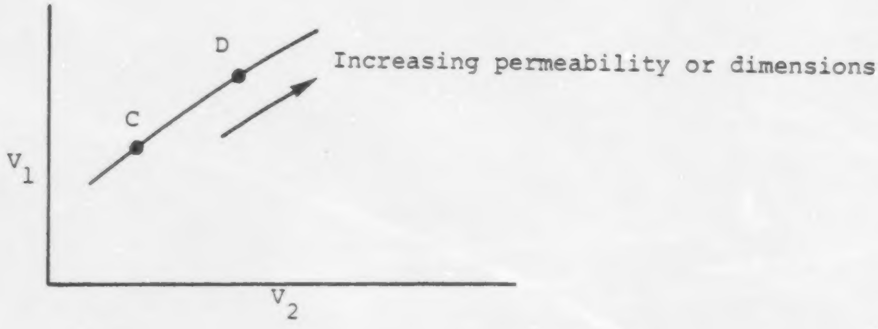
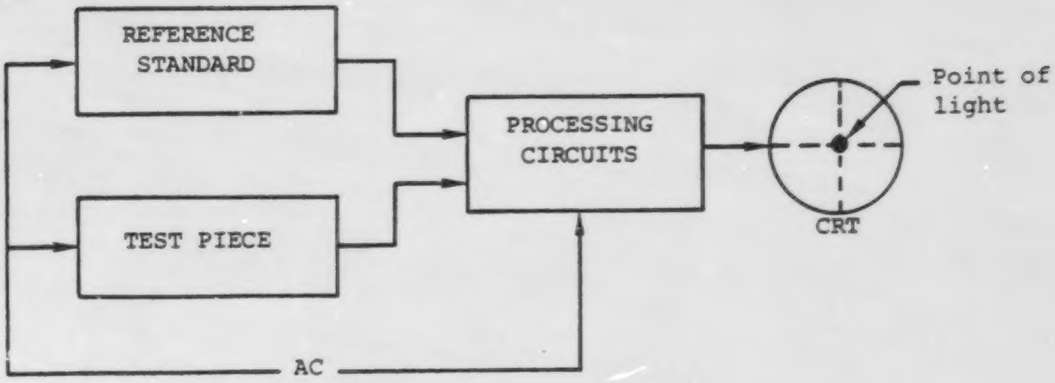


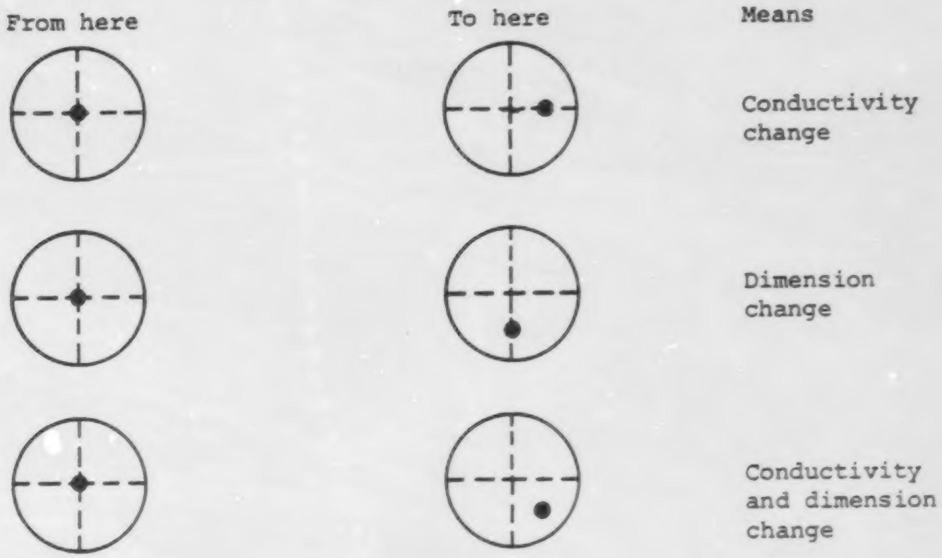
Figure 32-5-24. Ec Curve with Permeability and Dimensional Changes

By superimposing the plots of Figures 32-5-23 and 32-5-24, an important fact is realized. The direction of the coil's output with conductivity changes is essentially at a right angle to the direction of the coil's output with dimension and permeability changes. This fact permits processing circuits to separate the conductivity variable from the dimension and permeability variables. The dimension and permeability variables are inseparable because they cause a change in coil output in the same direction. Processing circuits use (1) vector point method, (2) ellipse method, or (3) linear time base method for phase analysis.

Phase Analysis - Vector Point Method

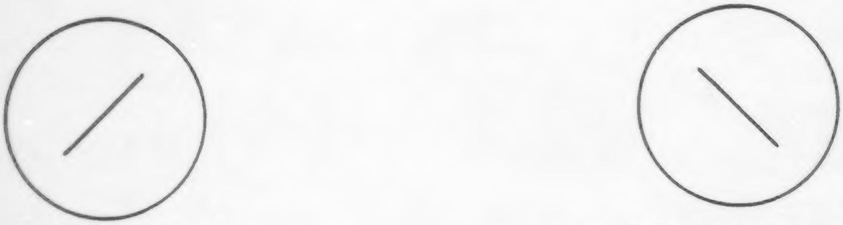
The vector point method of phase analysis controls a point of light on a cathode ray tube (CRT) as illustrated in Figure 32-5-25. The processing circuits supply a voltage representing the conductivity variable to one axis of the CRT (horizontal axis in the figure) and supply a voltage representing dimension and permeability variables to the other axis of the CRT (vertical axis in the figure). If properties of the test piece are identical to the reference standard, the point of light is positioned to the center of the CRT. Movement of the point of light in the horizontal direction represents changes in conductivity. Movement in the vertical direction represents changes in dimension or permeability. If the permeability of the test piece is considered equal to that of the reference standard, vertical movement represents dimensional changes.


REFERENCE STANDARD
TEST PIECE
PROCESSING CIRCUITS
Point of light
CRT
AC


From here
To here
Means
Conductivity change
Dimension change
Conductivity and dimension change

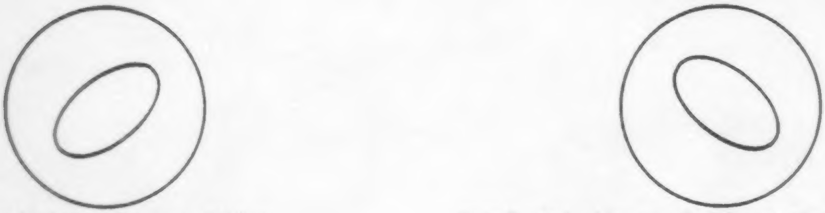
Phase Analysis - Ellipse Method

Phase analysis by the ellipse method provides the CRT patterns illustrated in Figure 32-5-26. This method uses two coils arranged for either external or self-comparison. When outputs of the coils are equal, the CRT indication is a straight line. Orientation of this straight line is adjusted to establish a reference position. Dimensional changes cause the straight line to rotate such that its orientation from the reference position is indicative of dimensional changes. Conductivity changes cause an ellipse to form whose size is proportional to the extent of conductivity change. Changes in both dimensions and conductivity form an ellipse at an orientation away from the reference position.



Reference Position Only

Dimensional Change Only



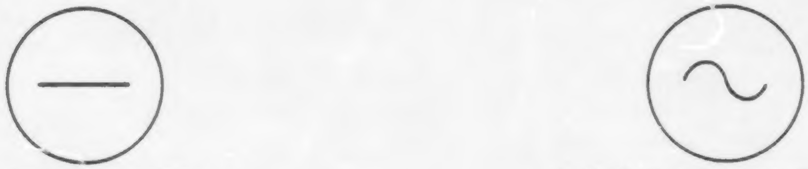
Conductivity Change Only

Conductivity and Dimensional Change

Figure 32-5-26. Ellipse Indications

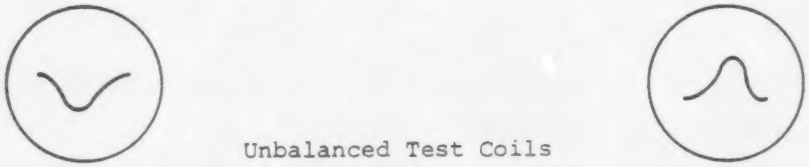
Phase Analysis - Linear Time Base Method

Phase analysis by the linear time base method uses a phase controlled timing voltage to establish the horizontal sweep on the CRT. The period of the timing voltage is equal to the time (period) of one cycle of output from the test coils. The output of the two test coils is applied to the vertical axis of the CRT. When no output exists, i.e., when the test coils are balanced, the CRT display is a horizontal line caused by the timing voltage. When the test coils are unbalanced, the output is reflected as a sinusoidal waveform on the CRT. Because the periods of the timing voltage and the test coil output are equal, one full cycle of test coil output appears on the CRT. The starting point of the cycle is selected by adjustment of the phase relationship of the timing voltage with respect to that of the test coil output. Figure 32-5-27 illustrates typical patterns.



Balanced Test Coils

Unbalanced Test Coils,
Inphase Timing to Output

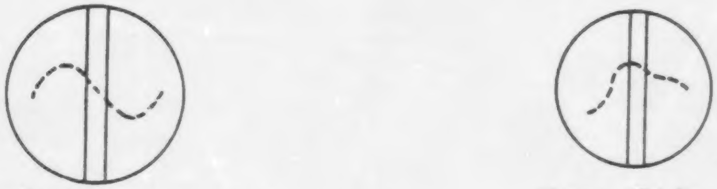


Unbalanced Test Coils
Out of Phase Timing to Output

Figure 32-5-27. Linear Time Base Signals

Linear time base processing circuits reflect changes in dimensions of the test piece as changes in amplitude of the sine wave and changes in conductivity as changes in phase of the sine wave. Thus, the system has capability of separating these variables.

A common technique for aiding in the interpretation of linear time base signals is the use of a slit placed over the CRT screen. As illustrated in Figure 32-5-28, only the portion of the sine wave visible in the slit is of concern. For measurements of conductivity, a known test piece is tested and the phase control is adjusted until the zero reference of the sine wave appears in the slit. If conductivity of additional test pieces differs from the known test piece, a phase shift occurs. This is seen in the slit as a change from the reference value. Dimensional changes would not cause a phase shift and therefore not be seen in the slit.



Inphase

Phase Shift

Figure 32-5-28. Use of Slit for Linear Time Base

Modulation Analysis

Modulation analysis uses relative motion between the test coil and the test piece and evaluates modulation of test coil output caused by this relative motion. A differential coil in the self comparison arrangement is affected by test piece characteristics as with other methods of eddy current testing. In addition, due to the relative motion, the rate of change in test coil output is proportional to the rate of change of the material variable causing the output. Thus, coil's output is modulated proportional to the rate of change of the material properties of the test piece.

Material properties vary over the length of the material at different rates. Thus, different modulation frequencies are caused by various properties. Dimensions of material forms, such as tubing, are typically very uniform, i.e., dimensions change very slowly along the length of the article. Thus, dimensional changes are characterized by very low frequency modulation. Chemical composition and heat treatment changes occur slowly and, therefore, cause low frequency modulation. Changes in lattice, caused by material processing such as cold working, occur over relatively small areas and, therefore, cause intermediate frequency modulation. Material discontinuities are typically small in size or have sharp boundaries and thus cause high frequency modulation.

Modulation analysis circuits contain electronic filters which permit display of frequency ranges. For example, selection of high frequencies for display results in indication of discontinuities and suppression of signals from other material properties. In addition, phase analysis circuits are typically included to suppress either conductivity or dimension effects. These performance characteristics make modulation analysis exceptionally good for detection of discontinuities because other variables are highly suppressed. However, speed control and alignment of the test piece with the test coil are essential in order to avoid false indications.

EXERCISES

1. Explain the relationship between permeability, magnetic flux density and intensity of the magnetizing force.

2. Explain the relationship between the number of turns and the spacing of turns of a coil to the inductance or inductive reactance of the coil.

3. Briefly describe how eddy currents are generated.

4. Describe the effects on eddy current by:
    a. magnetic field strength
    b. test frequency
    c. conductivity of the test piece
    d. permeability of the test piece

5. What are some of the factors which affect the conductivity of a metallic alloy?

6. Explain why eddy current testing of magnetic alloys must be performed with the alloy magnetically saturated.

7. Briefly explain the following regarding eddy current testing:
    a. lift-off effects
    b. fill factor effects
    c. fall-off effects
    d. end effects

8. Describe the physical arrangements of surface coils, including gap coils and spring loaded coils.

9. Briefly explain the use of differential coils in the self-comparison technique and the external comparison techniques.

10. Briefly explain the impedance analysis method of eddy current testing.

11. Compare and contrast the following:
    a. Vector point method of phase analysis
    b. Ellipse method of phase analysis
    c. Linear time base method of phase analysis

12. Describe modulation analysis and briefly explain its use.

MATERIALS

Not Applicable

PROCEDURES

Not Applicable

DATA TABLE

Not Applicable

REFERENCE MATERIALS

Hugo L. Libby, Introduction to Electromagnetic Nondestructive Test Methods, 1971, Wiley-Interscience

R. L. Brown, Inservice Examination of Heat Exchanger Tubing with Eddy Current NDT Equipment, HEDL-TME-75-29, National Technical Information Service, Springfield, Virginia

J. H. Flora, S. D. Brown, J. R. Weeks, Evaluation of the Eddy Current Method of Inspecting Steam Generator Tubing, 1976, National Technical Information Service, Springfield, Virginia

General Dynamics, Eddy Current Testing Classroom Training Handbook, General Dynamics, Convair Division, San Diego, California

Owen F. Hedden, Short Course on ASME Section XI Eddy Current Examination, 1979, American Power Conference

TEST

1. Define:

   a. permeability

   b. conductivity

   c. magnetic flux density

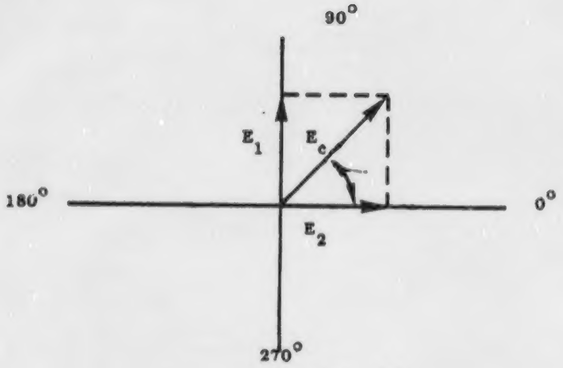
   d. inductance

   e. inductive reactance

2. Circle the letter of each of the following conditions which would provide for an increased inductive reactance.
   a. fixed coil, increased frequency
   b. increased number of turns per inch of coil length
   c. greater spacing between individual turns of wire
   d. double winding vice single winding.

3. Identify the following terms represented by Graph #1 below.
   a. E_1
   b. E_2
   c. Ec

d.



Graph #1

4. Referring to Graph #1, the illustrated plot is:
   - a. voltage plane
   - b. impedance plane
   - c. inductance plane
   - d. eddy current plane

5. Referring to Graph #1, circle the letter of each of the following conditions which would increase ϕ.
   - a. use of coil with greater inductive reactance but same resistance
   - b. addition of resistance to the circuit
   - c. rewinding the given coil such that closer spacing between turns is achieved
   - d. replacing the given coil whose ratio XL/R is 15 with a coil whose ratio XL/R is 10

6. Describe how eddy currents are generated.

7. Describe the effect on eddy current penetration depth by:
   - a. magnetic field strength
   - b. test frequency

  - c. conductivity of test piece

  - d. permeability of test piece

8. Name five factors which affect conductivity of a metallic alloy.

9. Describe why eddy current testing of magnetic alloys requires magnetic saturation of the alloy.

10. Describe the effects of:
    - a. lift-off

    - b. fill factor

    - c. fall-off

    - d. end effects

11. Describe the following coil techniques with respect to eddy current testing:
    - a. absolute coil

    - b. self-comparison differential coil

    - c. external comparison differential coil

12. Describe the following eddy current testing methods.
    - a. impedance analysis

    - b. vector point phase analysis

c. ellipse phase analysis

d. linear time base phase analysis

13. Describe how phase analysis circuits distinguisy between the conductivity variable and the dimension variable.

NUCLEAR TECHNOLOGY

MODULE 32 - 6

OPERATION OF EDDY CURRENT TEST EQUIPMENT

COURSE 32: NONDESTRUCTIVE EXAMINATION (NDE)

CORD

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

MODULE 32-1	Fundamentals of Ultrasonic Testing
MODULE 32-2	Operation of Ultrasonic Test Equipment
MODULE 32-3	Fundamentals of Magnetic Particle Testing
MODULE 32-4	Operation of Magnetic Particle Test Equipment
MODULE 32-5	Fundamentals of Eddy Current Testing
⇨ MODULE 32-6	Operation of Eddy Current Test Equipment

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INTRODUCTION

The Nuclear QA/QC Technician in the Operations Phase of pressurized water reactors is involved with eddy current examination of steam generator tubing. This examination is one of the more complex eddy current tests and one that is specifically required by regulation. Other involvement may occur at manufacturer's plants and for certain applications at the power plant site dependent upon local decisions.

This module details eddy current examination of steam generator tubing. In this regard, this module describes the equipment, calibration standards, calibration procedure, examination procedure, and test records associated with inservice inspection of tubing. The special effect of tubing supports is described and insight is given on interpreting test signals in the vicinity of tube supports.

In addition, this module describes other applications of eddy current testing. The calibration and testing techniques for these applications are described and their similarities with those used in inspection of steam generation tubing are indicated.

MODULE PREREQUISITES

The student/trainee should have prior training on fundamentals of eddy current testing, such as by completion of Module 32-5, Fundamentals of Eddy Current Testing. The student also shall have completed all previous modules of Course 32.

OBJECTIVES

Upon completion of this module the student/trainee can:

1. State the purpose of inservice examination of steam generator tubing.
2. Briefly describe the functions of typical eddy current test equipment including probe, test instrument, storage oscilloscope, strip chart recorder, and magnetic tape recorder.
3. Describe the calibration standard used in eddy current testing of steam generator tubing, including material type and shape, identification, and how flaws are made in the standard.
4. State the basic premise upon which calibration of the ET system is based.
5. State three conditions which require verification of calibration of the ET system.
6. Demonstrate calibration of an ET system using the manufacturer's technical manual.
7. Describe how a Phase Angle/Defect Depth Calibration Curve is constructed and state the use of this curve.
8. Describe the effect on defect signals by tube supports including a qualitative statement on severity of effect.
9. Name three basic types of applications of eddy current testing and give an example of each.

STEAM GENERATOR TUBING EXAMINATION

Purpose

Pressurized water reactors use steam generators to generate steam from the heat of reactor coolant while at the same time serving as a reactor coolant pressure boundary. With time, deterioration of tube walls can occur in the form of corrosion, pitting, and cracking. Individual tubes can eventually become "leakers" where the higher pressure reactor coolant leaks to the lower pressure steam cycle. Such leakers are plugged if leakage becomes excessive in order to maintain the integrity of the pressure boundary.

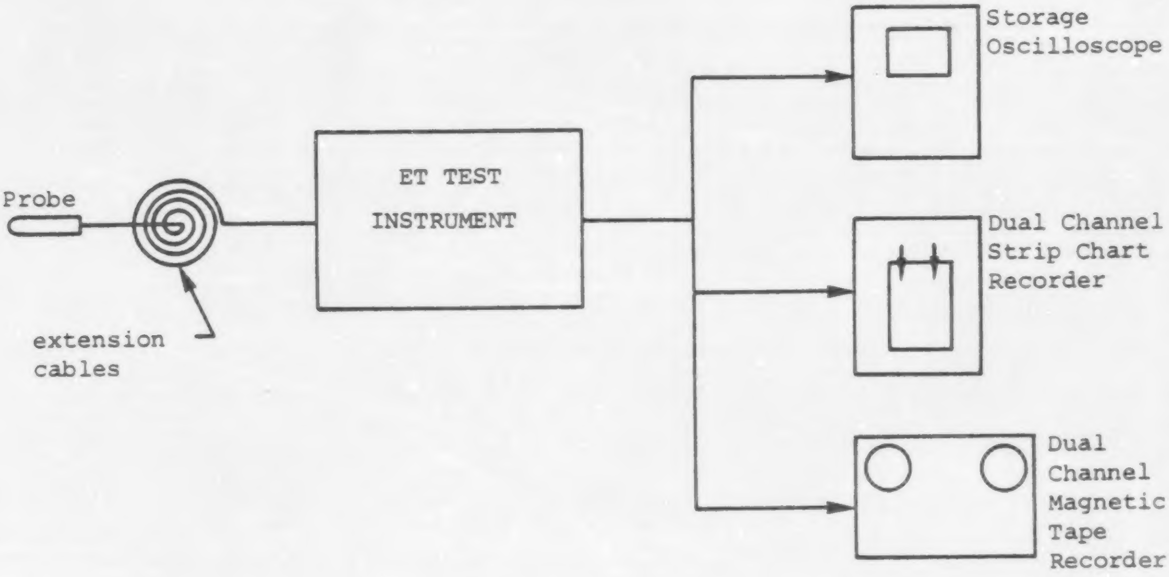
An examination method is needed which will detect leakers and potential leakers among the thousands of closely spaced tubes in a steam generator. Eddy current examination provides such capability for inservice examination of steam generator tubing.

Equipment

The equipment used for examination of steam generator tubing is identified by the block diagram in Figure 32-6-1.

Referring to Figure 32-6-1, the eddy current test system includes probe with cables, eddy current test instrument, storage oscilloscope, dual channel strip chart, and dual channel tape recorder.

The test probe may be either a differential coil or an absolute coil. The outer diameter of the coil should be almost equal to the inner diameter of the tubing in order to provide a high fill factor.



Storage
Oscilloscope
ET TEST
INSTRUMENT
Probe
Dual Channel
Strip Chart
Recorder
extension
cables
Dual
Channel
Magnetic
Tape
Recorder

Figure 32-6-1. ET Block Diagram

The test instrument provides an adjustable test frequency, vector point phase analysis circuitry, and phase and sensitivity controls. Test frequency controls typically consist of a coarse selector and fine tuner. The coarse frequency selector determines a range of frequencies, e.g., 1 KHz to 4 KHz, or 400 KHz to 1 MHz. The fine tuner permits selection of a specific test frequency within the range established by the coarse frequency selector. The phase analysis circuitry provides vertical and horizontal output signals to the storage oscilloscope, strip recorder, and tape recorder. The phase relationship of these output signals is proportional to the degree of unbalance of a bridge circuit containing the test coil. Therefore, the phase relationship of output signals primarily determines test interpretation as described later. A Phase or Rotation control on the test instrument permits rotating the displayed signal to a desired orientation.

A sensitivity control on the test instrument permits the adjustment of signal amplification in order to establish the desired sensitivity to defect signals.

The storage oscilloscope may be integral with the test instrument or it may be a separate device. The screen and circuitry of the cathode ray tube are such that continuous illumination of the vector point occurs until it is electronically erased. In this manner, the path of the vector point is made visible, or "stored". Horizontal and vertical position controls permit adjustment of the position of the displaced signal pattern to the desired area of the screen.

The dual channel strip chart recorder provides for easy correlation of defect signal to location of the defect along the length of the tube being examined. Dual channels provide independent tracing of the vertical and horizontal test signals. Controls typically include chart speed in terms of inches or millimeters per second, sensitivity in terms of volts per chart line, stylus position control for positioning each stylus to a desired reference, and trace width control.

The dual channel magnetic tape recorder permits re-analysis of the test at later times by play-back to the storage oscilloscope. Dual channels provide independent recording of vertical and horizontal test signals. Typical controls include Stop, Record, Pause and Gain.

Test System Procedure

Written procedures are used for eddy current examination of steam generator tubing. Each procedure provides sufficient instructions to permit adequate repeatability of results when used by different persons. The procedure identifies (1) tube material, diameter, and wall thickness, (2) size and type of test probe including manufacturer's name and part number, (3) test frequency, (4) type and model of ET test instrument,

(5) scanning direction and speed during examination, (6) description of inspection technique, (7) description of calibration procedure and calibration standard, (8) description of data recording equipment and procedures, and (9) procedure for interpretation of test results and the applicable criteria for reportable indications.

The preparer of the test procedure ensures that optimum conditions are specified to permit proper testing. As a minimum the examination must be conducted in such a manner that the indication from a flaw penetrating 20% or more of the tube wall is readily discernible from probe motion, flaw detection adjacent to supporting members is optimized, measurement error is minimized, and consistent test results are achievable. Key considerations for ensuring this capability are:

- selection of test equipment which meets the accuracy and linearity requirements specified by Section XI of the ASME Boiler and Pressure Vessel Code.
- selection of test frequency which gives depth of penetration greater than tube wall thickness but which optimizes flaw detection in the vicinity of tube supports. It should be recalled that depth of penetration decreases as test frequency increases.
- scanning speed which does not produce changes in test signal at higher frequency than the response frequency of the test equipment. Where equipment frequency response meets the specified minimum of d-c to 100 Hz, maximum scanning speed is fourteen inches per second.
- use of correct calibration standard and calibration procedures.
- use of correct technique for interpreting test results.

Calibration Standards

Calibration standards are used to calibrate the eddy current test system. The calibration standard is made from a length of tubing of the same size and material type as that to be examined in the steam generator. The length of tubing is examined by ultrasonic and liquid penetrant testing to ensure that its quality is equivalent to that for acceptable new tubing for the steam generator. Each standard is identified by a serial number and is traceable to the manufacturer's heat number. Holes and grooves are machined on the standard in accordance with the schedule identified by Figure 32-6-2.

Calibration of ET System

The ET system is calibrated as a complete entity. Any change in the ET system is cause for recalibration. Therefore, any change of test probe, extension cables, ET instrument recording instruments, or any other parts of the ET system requires recalibration.

Inservice inspection requirements for steam generator tubing stipulate that the ET system be calibrated prior to use and that its calibration be verified (1) at the beginning and end of each side of magnetic tape, (2) the beginning and end of each strip chart roll, and (3) at four hour intervals maximum. If any of the verifications of calibration finds an out-of-calibration status, the ET system is recalibrated and the data interpreter determines which tubes, if any, will be retested. The need for retesting is dependent on the extent of out-of-calibration status and the results of tests since the last in-calibration status.

Calibration Holes and Grooves

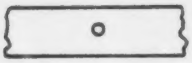
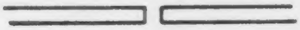
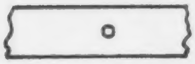
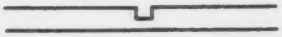
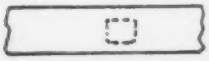
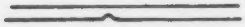
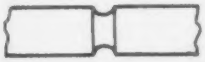
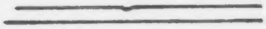
Description	Top View	Cross-sectional View
through-wall drilled hole (0.052" dia. for 3/4" O.D. tubing and smaller; 0.067" dia. for larger tubing)		
flat-bottomed drilled hole 5/64" dia. x 80% through from outer wall surface		
flat-bottomed drilled hole 7/64" dia. x 60% through from outer wall surface		
flat bottomed drilled hole 3/16" dia. x 40% through from outer wall surface		
four flat bottomed holes, 3/16" dia. spaced 90° apart around tube circumference, 20% through tube wall		
circumferential groove, 360°, 1/16" wide, 20% through from the inner wall surface		
circumferential groove, 360°, 1/8" wide, 10% through from the outer wall surface. (for absolute coils only)		

Figure 32-6-2. Calibration Standards

Differential Coil Calibration

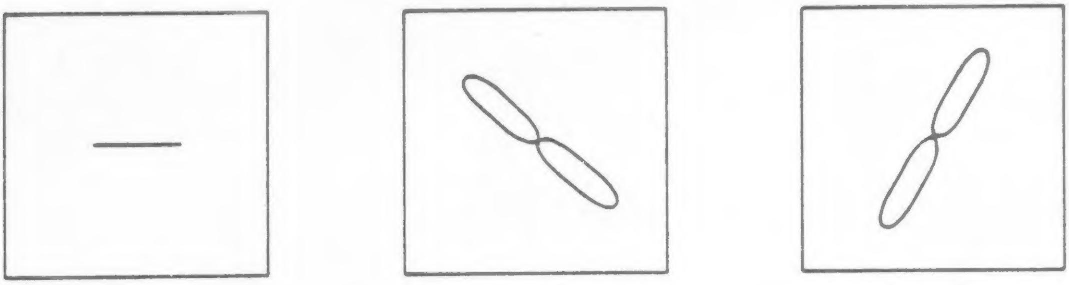
ET systems using a differential probe are calibrated using the through wall drilled hole in the standard. The calibration steps and acceptance criteria are listed in Table 32-6-1.

TABLE 32-6-1. Differential Coil Calibration

Calibration Step	Acceptance Criteria
Set ET instrument at test frequency and position probe to produce maximum response from through wall drilled hole. Adjust sensitivity and gain controls as necessary.	Response from through wall drilled hole produces a signal at least 50% of full CRT screen height.
Position probe to defect-free section of the standard. Adjust "null" controls as necessary (Note 1).	Vector point centered on CRT in null condition
Move probe within defect-free section of the standard. Adjust phase or rotation control as necessary.	Horizontal response is obtained from probe motion.
Withdraw the probe past each artificial flaw in the standard and record responses on magnetic tape, strip chart, and CRT. Adjust test frequency and repeat calibration as necessary.	Response from through wall drilled hole is 40° ± 5° from the horizontal. Response from 20% flat bottomed drilled hole is 120°, + 10°, -30° phase rotated from the through wall hole test signal
NOTE 1: Null controls adjust sensitivity of the test instrument and typically include Sensitivity, Horizontal Balance, and Vertical Balance. Some instruments automatically null upon depressing Auto-Null control.	

The calibration listed in Table 32-6-1 results in setting three test parameters. First, the test instrument is nulled against an acceptable portion of tubing. Therefore, any signal responses are theoretically from changes in material properties away from those which are acceptable. Second, the signal response due solely to probe motion is established in the horizontal direction. Such response is due to probe "wobble" which causes a response signal due to variations in fill-factor. This variation is primarily due to dimensional changes and thus establishes the horizontal axis of the CRT as the dimensional variable. Third, the signal response from the through wall drilled hole is established at a known phase relationship. Through wall actual defects should share this phase relationship. In essence, the vertical axis of the CRT has been established for the conductivity variable. The combination of dimension and conductivity changes from a through wall defect give a known phase rotation.

The phase relationships of typical responses to actual defects are illustrated in Figure 32-6-3. As indicated in detail (a) of the figure, probe wobble appears on the CRT as a horizontal indication. Through wall defects appear as indications rotated about 40° from the horizontal. Defects extending from the outer surface of the tubing but not through wall cause a larger phase rotation which is dependent primarily upon depth of the defect from the outer wall. Ordinarily, tubing defects do not originate from the inner wall. However, the ET system would detect such defects, if present, and display them as somewhere between the horizontal and about 40° clockwise.



(a) Probe Wobble

(b) Through Wall

(c) Partially through wall from outside surface

Figure 32-6-3. Typical Defect Signal Patterns

The actual depth of partially through wall defects is determined from a Phase Angle/Defect Depth Calibration Curve. This curve is constructed by the last calibration step listed in Table 32-6-1 by plotting the signal responses against the known depths of the drilled holes in the calibration standard. A typical curve is illustrated in Figure 32-6-4. Using this curve, the signal pattern of detail (c) of Figure 32-6-3 indicates a 120° phase angle which equates to a 64% depth of the defect.

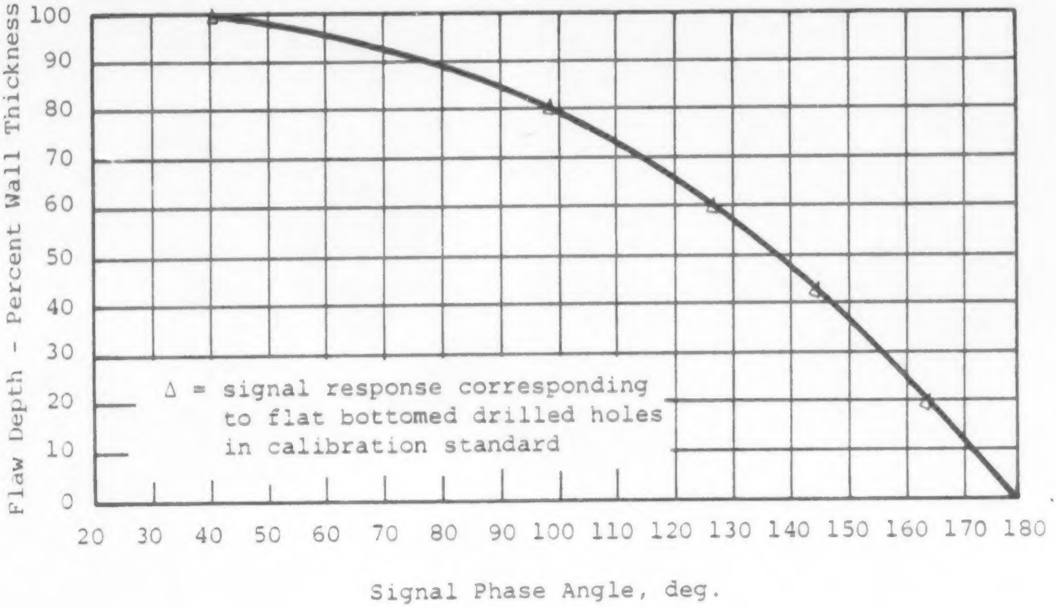


Figure 32-6-4. Phase Angle vs. Flaw Depth Inconel Tube 400 KHz (Typical)

Absolute Coil Calibration

An ET system which uses an absolute coil as the test probe is calibrated using the through wall hole and outer diameter circumferential groove of the calibration standard.

The calibration steps and acceptance criteria are listed in Table 32-6-2.

TABLE 32-6-2. Absolute Coil Calibration

Calibration Step	Acceptance Criteria
Set ET instrument to specified test frequency and position probe in calibration standard to maximum response from through wall drilled hole. Adjust sensitivity or gain as necessary.	Response from through wall drilled hole is at least 50% of full CRT screen height.
Position probe to section of standard free of artificial defects. Adjust "null" controls as necessary.	Vector point is centered on CRT.
Position probe to obtain maximum response from 1/8 inch wide outer diameter circumferential groove. Adjust phase or rotation control as necessary.	Indication is vertically downward on CRT.
Position probe to obtain maximum response from through wall drilled hole. Adjust frequency and/or repeat calibration procedure as necessary. Adjust amplitude as necessary.	Tangent from the end of the through wall signal intersects Y - axis at a 90° angle. Through wall signal amplitude is at least 30% of CRT screen height.
Withdraw probe through calibration standard, record responses on magnetic tape and strip chart, and verify signal responses on CRT.	CRT responses reflect proper phase rotation.

Calibration of the absolute coil results in setting the same parameters described previously for the differential coil. However, the signal patterns from the absolute coil are markedly different as illustrated in Figure 32-6-5. As illustrated, outside diameter defects result in a downward deflection where shallow outside defects appear vertically downward. A through wall defect provides a signal whose tangent from its tip intersects the y-axis by a 90° angle. A defect on the inside wall appears essential as horizontal deflection and probe wobble causes a signal direction which is essentially at a right angle to the direction of other signals. A Phase Angle/Defect Depth Calibration Curve is constructed in similar manner to that for the differential coil.

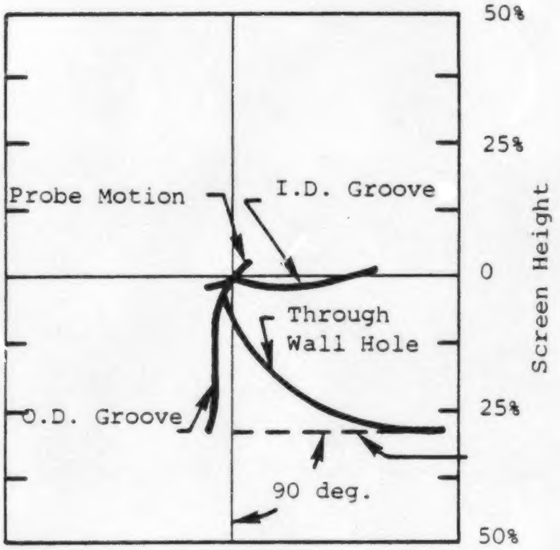
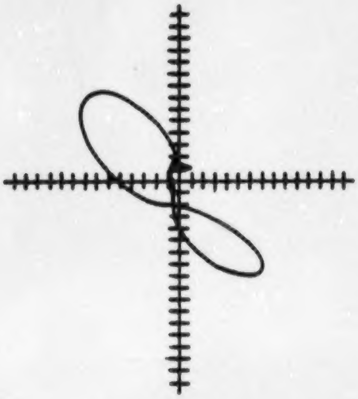


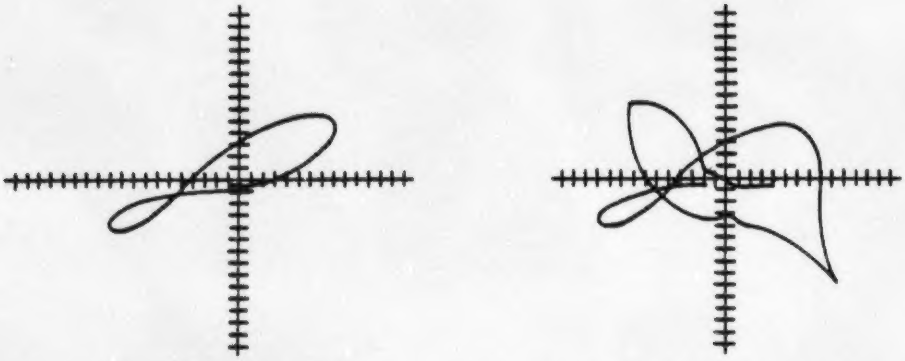
Figure 32-6-5. Typical Signals from a Properly Calibrated Absolute Coil Probe System

Effect of Tube Supports

Lateral support of steam generator tubing is provided at various intervals along the length of the tubes by tube supports. These tube supports cause a signal response which significantly interferes with the signal response of a defect in the vicinity of the tube support. Such interference makes difficult accurate data interpretation of defect signals in the vicinity of tube supports. The difficulty is illustrated in Figure 32-6-6.



(a) Tube Support Only



(b) Shallow Outer Diameter Defect Only

(c) Shallow Outer Diameter Defect In Vicinity of Tube Support

Figure 32-6-6. Tube Support Effect on Signal Responses

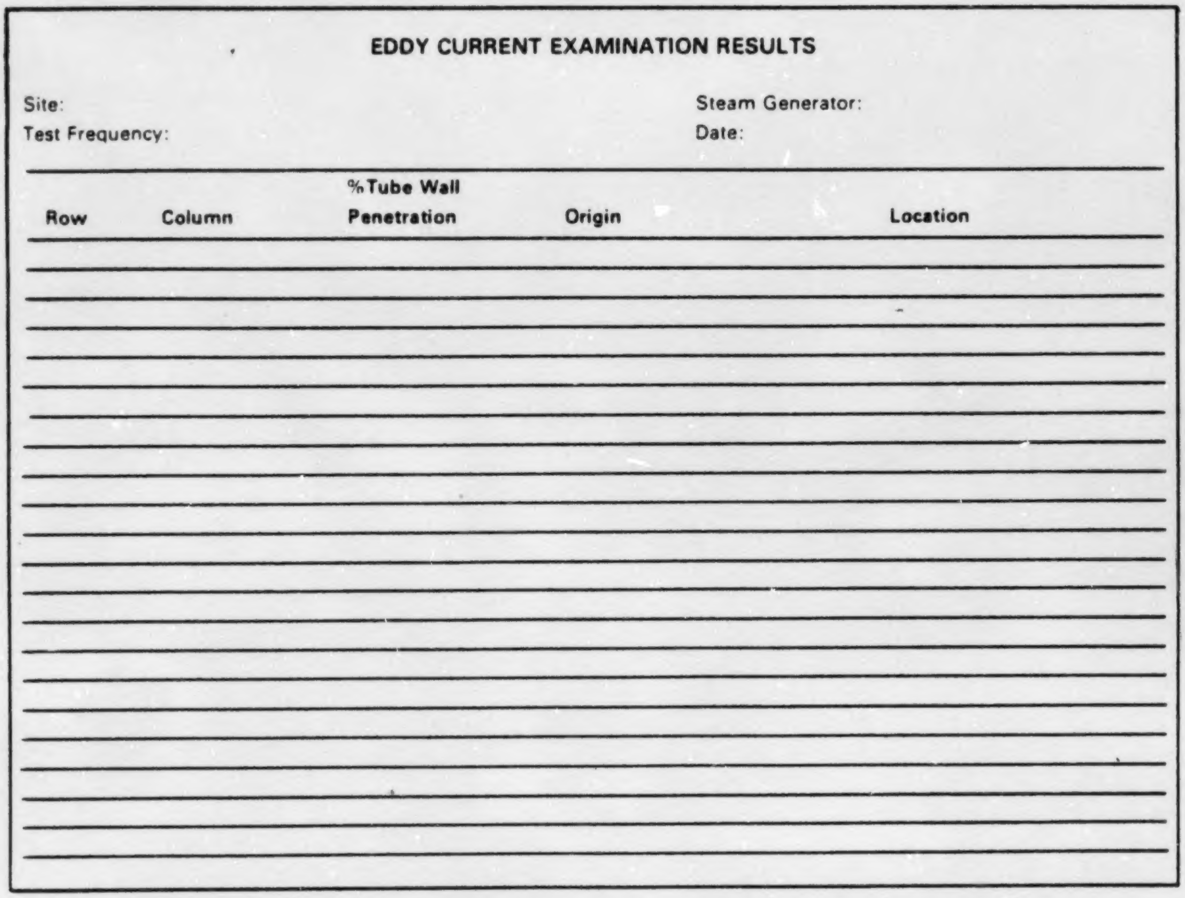
The data interpreter is faced with recognizing the effect of tube supports and discerning such effects. The ability to accurately interpret signal responses is primarily affected by the amplitude of the defect signal. Figure 32-6-6 indicates that a tube support only signal differs enough from a through wall defect signal to make it discernable. The figure also indicates that a partially through defect signal superimposed on a tube support signal is discernable if the defect signal is of sufficient amplitude as is the case in detail (c). Defects in the vicinity of tube supports whose signal amplitude is low will probably not be discernable. Such limitations are minimized by use of optimum test frequency and proper calibration.

Records

Records of inservice ET examination of steam generator tubing consist of magnetic tape and strip chart recordings and Report Form NIS-BB. Identification of tubing and ET systems represented is placed on these recordings by "voice over" and "pen-and-ink" entries. Identification must include the following:

- name of Owner
- plant site
- steam generator identification
- date of examination
- test frequency
- reel number and side
- calibration standard identification
- operator's name, certification level, and company affiliation
- each tube represented by tube numbering system

Report From NIS-BB is recommended by Section XI of the ASME Boiler and Pressure Vessel Code. This form is illustrated in Figure 32-6-7.



EDDY CURRENT EXAMINATION RESULTS

Site:

Test Frequency:

Steam Generator:

Date:

Row	Column	%Tube Wall Penetration	Origin	Location

Figure 32-6-7. Form NIS-BB, Tube Examination Report

Additional Eddy Current Test Applications

General

Eddy current testing is continuously being more diversely applied. While it is impractical to describe all applications, discussion of the types of applications gives insight to the versatility of eddy current detection.

It should be recalled that eddy current testing examines material to a relatively shallow depth and is sensitive to all factors affecting conductivity and permeability of the material. It is also sensitive to the dimensional relationship between the test probe and the test piece. While sensitivity to so many factors makes eddy current testing somewhat complex, it also permits various uses of eddy current testing. Among the more popular uses of eddy current testing are (1) flaw detection, (2) metal sorting, and (3) coating thickness measurements.

Flaw Detection

Detection of flaws in materials, parts, and components used in nuclear power plants is typically accomplished by one or more of radiography, liquid penetrant, magnetic particle, and ultrasonic testing. However, when these methods prove to be extremely difficult to apply, eddy current testing often provides a solution. The previous description of eddy current testing of tubing in installed steam generators is an obvious example. Other instances which may warrant eddy current testing for defects include examination of (1) small bore through holes and blind holes, (2) shots and grooves, and (3) contoured surfaces susceptable to fatigue cracking.

A variety of eddy current test instruments are available for flaw detection. Those instruments used for tubing inspection are also suitable for other applications by using appropriate probes. Such probes may be either absolute or differential and are selected to provide proper lift-off or fill-factor. Either a microammeter or a storage oscilloscope provide readout. Instruments with a microammeter readout are calibrated with a standard to determine expected currents with and without a flaw present. For example, readout for sound metal might be 90μa while readout for a crack open to the surface might be 20μa. A system which uses an absolute surface contact coil and a storage oscilloscope might be calibrated to provide the response illustrated in Figure 32-6-8. In all cases, of flaw detection, calibration procedures similar to those in Table 32-6-1 or Table 32-6-2 are used to establish the test system response.

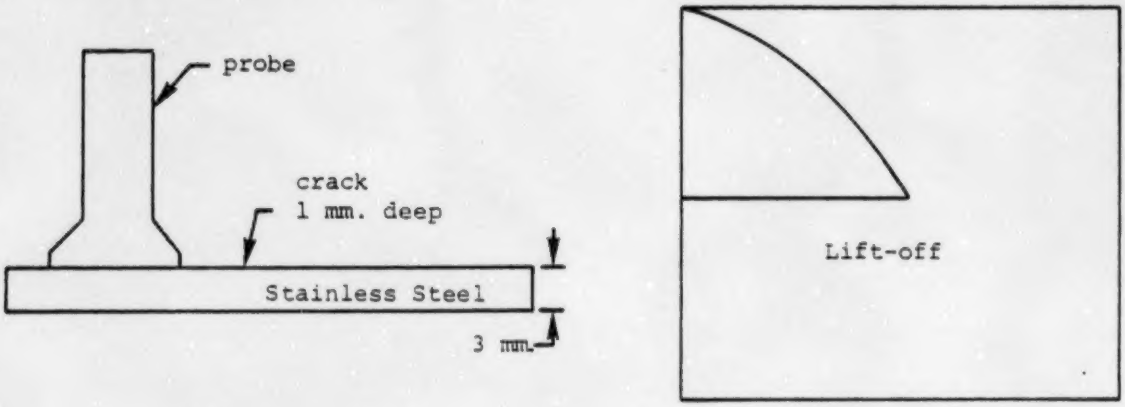


Figure 32-6-8. Flaw Detection with Surface Contact Probe

Metal Sorting

Early application of eddy current testing for metals sorting served as a nondestructive means of determining if material mix-ups had somehow occurred. Or, if a mixup was discovered, eddy current testing provided a means of segregating the material. Continued use and expansion of such testing has occurred as sensitivity of ET system has improved.

All metals sorting tests depend on the ability of the ET system to distinguish among conductivities of various materials. It should be recalled that materials of different types and of different grades within a type usually have different conductivities although some overlapping of conductivity does occur. Also, for a given type and grade of material, conductivity is affected by processing of the material such as by cold working and heat treating. In addition, parts in service often exhibit a change in conductivity with service life due to such factors as age hardening or self-annealing. Thus, the following are illustrative examples of uses of eddy current testing for metal sorting:

- detection of incorrect material within a lot. This test is used by manufacturers and receivers of product where there is a definite probability of inadvertant mixup of material type. It is particularly used where large quantities of items are processed on a lot basis e.g., wire products, and threaded fasteners. Figure 32-6-9 illustrates a typical memory oscilloscope pattern.
- sorting of parts by hardness. This test is used to determine if hardness requirements for heat treated parts are met. It is also used to sort given parts by hardness values. A typical signal pattern is illustrated in Figure 32-6-10.
- sorting of parts in service. This test is useful as an aid to maintenance for parts susceptible to age-hardening or self-annealing in service. In such cases, a relationship exists between service hours and test signal patterns as illustrated in Figure 32-6-11. Where sufficient data is obtained to permit correlation between test signal response values and maximum normal

lifetime of the part without failure, the test can determine the need for maintenance prior to failure of the part.

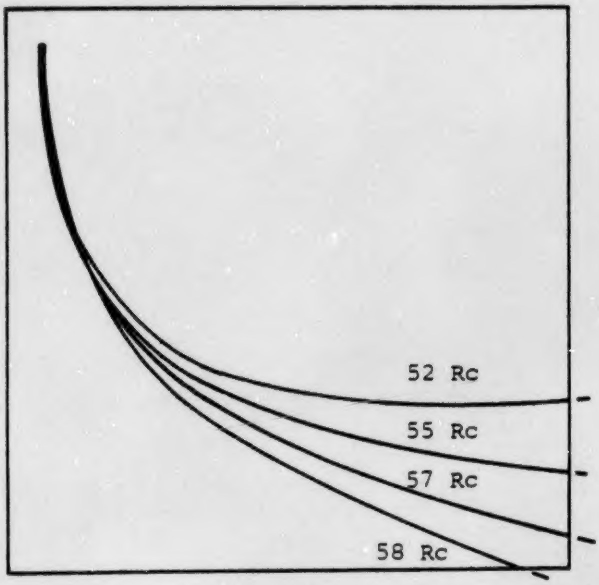


Figure 32-6-9. Signal Pattern for Sorting of Nickel-Chrome-Iron Alloy from Stainless Steel Alloy

Coating Thickness Measurements

Eddy current testing measures thickness of coatings by the lift-off or fill-factor effects. Such tests can also measure corrosion film thickness in many instances. In all cases, the substrate must be conductive while the coating may be either conductive or non-conductive. Conductive coatings are exemplified by platings such as chromium, nickel, gold, and silver plating. Nonconductive coatings are exemplified by paints.

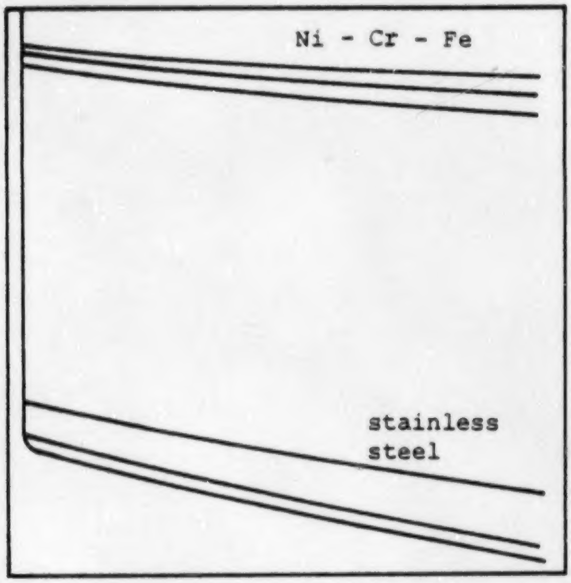


Figure 32-6-10. Signal Pattern for Hardness Sorting

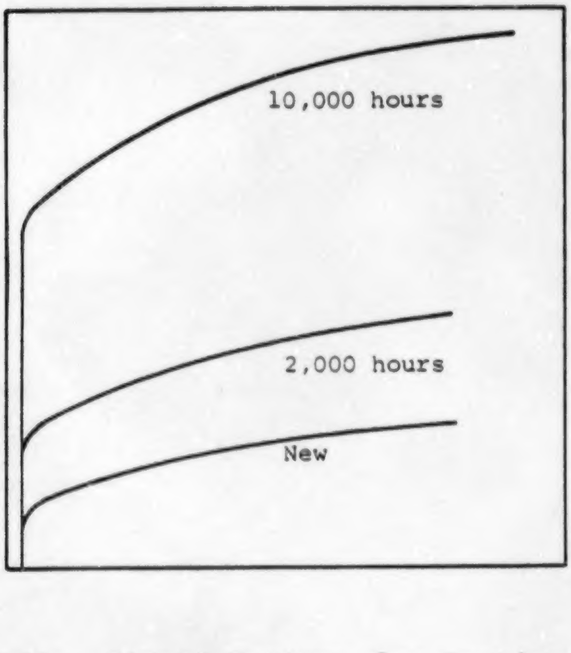
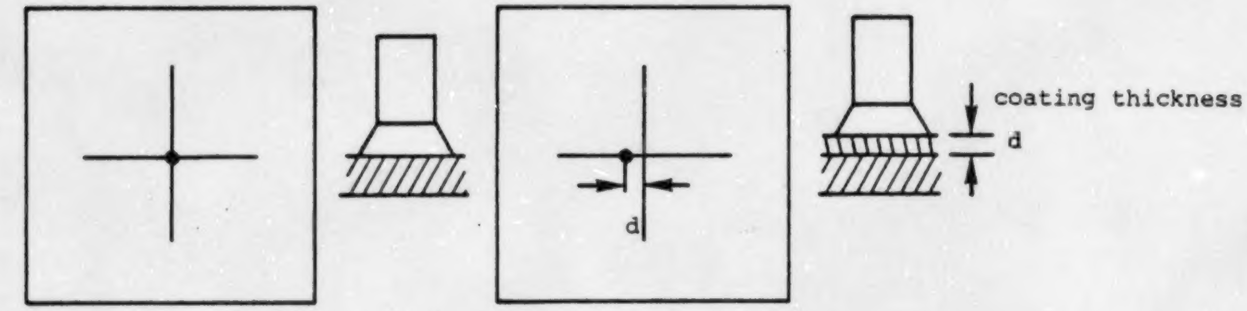


Figure 32-6-11. Signal Pattern for Sorting By Hours of Service

Thickness measurements require calibrating the ET system with standards of known coating thicknesses and of identical materials as the test pieces. Where an oscilloscope is used, phase or rotation control is adjusted such that variations in coating thickness occurs in the horizontal direction as illustrated in Figure 32-6-12. Some ET systems designed specifically for coating thickness measurements have a digital readout in 0.001 inch increments or less of coating thickness.



Probe on bare material only

Probe on a coating atop base

Figure 32-6-12. Signal Pattern for Coating Thickness Measurements

EXERCISES

The following exercises serve to reinforce the material presented in this module.

1. Familiarize yourself with an Eddy Current Test System as outlined in the Procedures section of this module. Then calibrate the ET System.

2. Perform an Eddy Current Test on tubing made from either nickel-chrome-iron or austenitic stainless steel as outlined in the Procedures section and specified in the Materials section of this module.

3. Perform a coating thickness measurement on painted standards with a known coating thickness as specified in the Procedures section of this module.

4. Answer the following questions as either true or false:

____ a. Eddy current examination provides a practical method of inspecting tubing of installed steam generators to detect flaws which cause or can eventually cause leaks of primary coolant.

____ b. The ET system for steam generator tubing is comprised of probe, extension cables, test instrument, storage oscilloscope, strip chart recorder, and magnetic tape recorder.

____ c. The probe may be absolute or differential and is shaped to enter the inside diameter of tubing with a large fill-factor.

____ d. The test instrument includes a bridge circuit, vector point phase analysis, and controls for sensitivity, frequency, position, and rotation.

____ e. The storage oscilloscope provides for continuous illumination of the vector point which provides the signal pattern for operator observation.

____ f. The strip chart recorder is dual channel and provides the ability to correlate defect signals with the date that the Eddy current examination was performed.

____ g. The magnetic tape recorder is dual channel and provides for signal interpretation at any later time by playback to a computer.

____ h. Eddy current examination of steam generator tubing must (1) discern a flaw of 20% or more of wall thickness from probe wobble, (2) optimize flaw detection adjacent to tube supports, (3) minimize measurements error, and (4) achieve consistent test results.

____ i. The objectives of the eddy current test procedure are met by (1) using equipment of specified accuracy and linearity, (2) selection of optimum test frequency, (3) use of proper scanning speed, (4) use of correct calibration standard and calibration procedure, and (5) use of correct technique for interpreting test results.

____ j. Calibration standards consist of a length of tubing of equivalent quality as new tubing and having drilled holes and grooves of known sizes and depths. Each standard is identified by serial number and is traceable to the manufacturer's heat number.

____ k. Eddy current test systems are accurately built and only need to be recalibrated twice a year.

____ l. Calibration sets sensitivity, reference position with no defects, and extent of phase rotation with known defects. It confirms use of optimum frequency or indicates the need to recalibrate with a different frequency.

____ m. Calibration must be verified at (1) beginning and end of each side of magnetic tape, (2) beginning and end of each strip chart roll, and (3) at four hour intervals maximum.

____ n. The Phase Angle/Defect Depth Calibration Curve is constructed by plotting signal responses from known defects and use in interpreting test results for depth of flaws.

____ o. Tube supports cause a signal pattern which greatly interferes with interpretation of test results. Amplitude of flaw signals primarily determines the ability to discern them from tube support signals. Use of a light weight probe and skilled operator minimize the effect of tube supports.

____ p. Records are provided by the strip chart and magnetic tape recordings. Identification of exact tube represented is added by pen-and-ink chart entries and voice-over on tape.

____ q. Eddy current testing is applied to (1) flaw detection, (2) metals sorting, and (3) coating thickness measurements.

____ r. Flaw detection provides the capability to detect flaws open to or near the surface and flaws on either side of thin-walled members as well as deep flaws.

____ s. Metals sorting uses the conductivity variable and has a variety of applications including verification of material identity, heat treatment condition, and aging in service.

____ t. Coating thickness measurements use the dimensional variable through lift-off or fill-factor effects and has applications of measuring thickness of conductive and nonconductive coatings and corrosion films.

MATERIALS

The following materials are required to support this module:

1. Eddy current test system comprised of (a) probe, (b) instrument cable, (c) test instrument, and (d) storage oscilloscope and with copies of the manufacturer's technical manual. Either of the following suffices:
    a. Automation Industries, Inc.; Sperry Products Division
        1) Multitest EM-3300 Eddy-Current Test Instrument
        2) Differential bore probe, with extension cable and of a diameter compatible with diameter of tubing selected (0.720 to 0.740 for tubing listed below)
        3) Absolute surface probes, 44B-022-3 and 44B-022-4
    b. NORTEC Corporation
        1) Eddyscope NDT-6D
        2) Differential I.D. probe, with extension cable and of a diameter compatible with diameter of tubing selected (0.720 to 0.740 for tubing listed below)
        3) Absolute SP Series surface probes
2. Several short lengths of tubing preferably with natural flaws of either:
    a. Nickel-Chrome-Iron, alloy 600 to ASME SB-163 or ASTM 8-163, 0.875 inch outside diamter, 0.050 inch nominal wall thickness
    b. Austenitic stainless steel to ASME SA-213 or ASTM 213, any of grades T2, T11, T12, or T17, 0.875 inch outside diameter, 0.050 inch nominal wall thickness
3. Tubing standard consisting of one short length of tubing with drilled holes in accordance with the schedule in Figure 32-6-2 of this module.

4. Painted metallic pieces suitable for coating thickness measurements.
5. Painted standards with known coating thickness.

PROCEDURES

The following procedures reinforce the information presented in this module.

1. Calibrate an ET system for tubing inspection as follows; record results on Data Table 32-6-1:
   a. Obtain from the instructor the manufacturer's technical manual for the ET equipment and familiarize yourself with the operating controls of the equipment.
   b. Energize the equipment in accordance with the manufacturer's technical manual and allow the recommended warm-up time.
   c. Obtain from the instructor a tubing standard. Record the identification number of the standard.
   d. Install a differential probe designed for insertion into the inner diameter of the standard by connecting the probe and its extension cable to the PROBE connector on the test instrument. Record probe identification number.
   e. Insert probe into standard to a section void of defects and set test frequency to 400 KHz. (Note: If test frequency is not continuously variable for the test instrument, select the frequency nearest 400 KHz.) Record test frequency.

f. Null the test instrument in accordance with the manufacturer's technical manual. Ensure vector point is centered on the oscilloscope.

g. Withdraw and insert test probe in standard within a section void of defects and observe direction of signal response from probe wobble. Adjust PHASE or ROTATION as necessary to obtain horizontal direction of signal response.

h. Position probe in standard to maximize response signal from through wall drilled hole. Adjust SENSITIVITY or GAIN to obtain signal response at least equal to 50% of screen height. Measure angle of signal pattern from the horizontal. If the angle is not within 40° ± 5°, repeat steps e, f, g, and h. If the angle is still outside limits, adjust frequency to bring it within limits and repeat steps f, g, and h. Record angle and new test frequency.

i. Withdraw probe by each drilled hole and plot test results to establish a Phase Angle/Flaw Depth Calibration Curve.

2. Eddy current test tubing as follows; record results on Data Table 32-6-2:

   a. Calibrate the ET system in accordance with Procedure #1.

   b. Obtain tubing from the instructor.

   c. Insert probe full length and scan tubing by manually withdrawing the probe at a rate not in excess of fourteen inches per second; constantly observe oscilloscope for flaw indications.

   d. For each flaw indication, measure phase angle and determine flaw depth using the Phase Angle/Flaw

Depth Calibration Curve. Record phase angle and depth and an estimated position along the length of tubing for each flaw.

e. Place a metallic object around a section of tubing to simulate a tube support.

f. Withdraw probe past the simulated tube support and observe signal pattern. Record features of this pattern which makes it discernable from flaw indications.

g. Place the simulated tube support adjacent a flaw in the tubing. Repeat step f and record results.

3. Measure coating thickness by eddy current examination as follows; record results on Data Table 32-6-3.

   a. Obtain from the instructor a painted metallic object, painted standards, and ET instrument technical manual. Record identification of standards.

   b. Energize the ET equipment in accordance with the manufacturer's technical manual and allow recommended warm-up time.

   c. Connect an absolute surface probe to PROBE connection on the ET instrument.

   d. Place probe on unpainted section of either standard or test piece and set test frequency at 1000 KHz.

   e. Null the test instrument in accordance with the manufacturer's technical manual.

   f. Lift probe off unpainted section and observe signal pattern. Adjust PHASE or ROTATION to obtain lift-off response in horizontal direction.

   g. Place probe on standard with thinnest coating thickness. Adjust GAIN or SENSITIVITY such that response aligns with a division on the CRT. Successively examine coating thickness on other standards and construct a calibration curve by plotting known thickness and measured response.

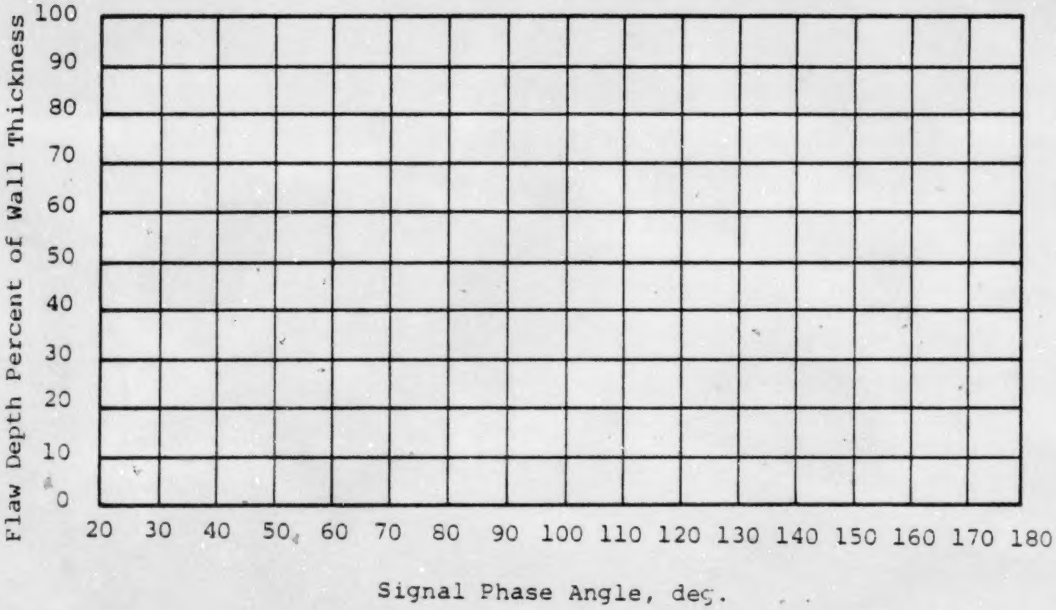
h. Examine test pieces and determine coating thicknesses by comparing signal responses with the calibration curve constructed in step g. Record results.

DATA TABLE

Date Table 32-6-1

Calibration of ET System for Tubing Inspection

Standard:____________________ Probe:____________________________
Test Frequency:_____________ Angle of 100% Hole Signal:______



Data Table 32-6-2
ET Examination of Tubing

Test Frequency ______________ Date ____________ Operator ______________

Tube Identification	Flaw % Wall Thickness	Flaw Location

Description of Tube Support Signal Pattern: ________________________

____

____

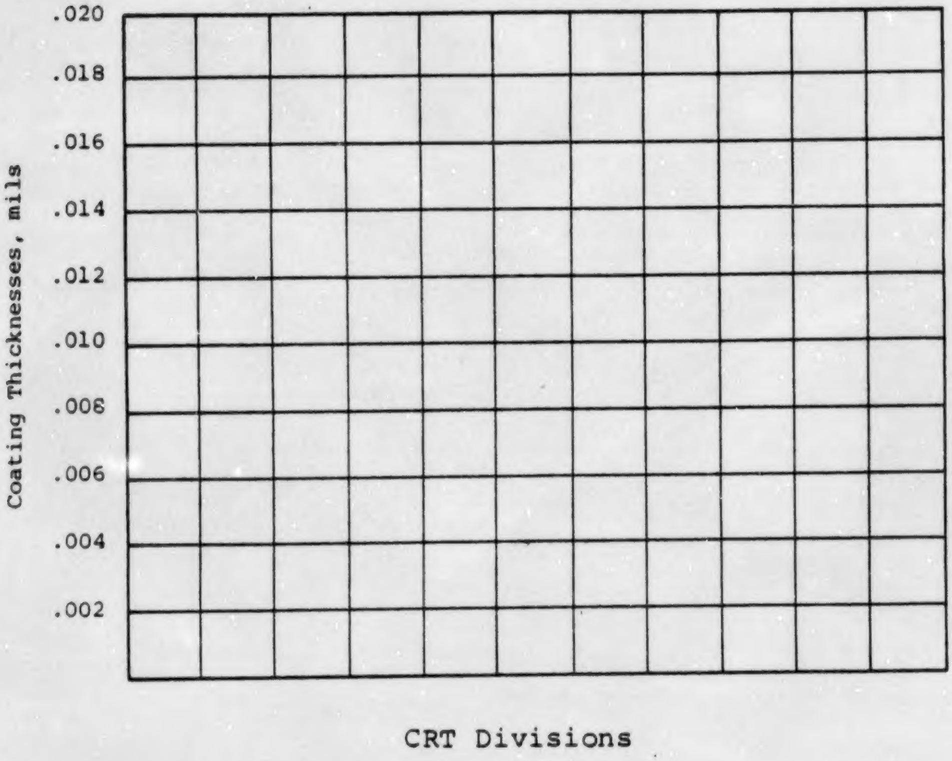
Effect of Tube Support on Flaw Signal: ________________________

____

____

Data Table 32-6-3

Eddy Current Measurement of Coating Thickness



(Label to match CRT screen)

Examination Results:

Test Piece	Coating Thickness	Location of Measurement

REFERENCE MATERIALS

Libby, Hugo L., *Introduction to Electromagnetic Nondestructive Test Methods*, 1971, Wiley-Interscience

ASME, *Boiler and Pressure Vessel Code, Section V, Nondestructive Examination, and Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components*, 1978, The American Society of Mechanical Engineers

J.H. Flora, S.D. Brown, and J.R. Weeks, *Evaluation of the Eddy-Current Method of Inspecting Steam Generator Tubing*, BNL-NUREG-50512-R, October 1976, National Technical Information Service

R.L. Brown, *Inservice Examination of IHX Tubing with Eddy Current NDT Equipment*, HEDL-TME 75-29, 1975, National Technical Information Service

TEST

1. State the purpose of inservice examination of steam generator tubing.

2. Briefly describe the functions of the following apparatus of eddy current test equipment used for examination of steam generator tubing.

   a. probe

   b. test instrument

   c. storage oscilloscope

   d. strip chart recorder

   e. magnetic tape recorder

3. Describe the physical appearance of the calibration standard used in eddy current examination of steam generator tubing.

4. How are flaws made in the calibration standard of question #3?

5. What is its purpose of the through-wall hole in the standard of questions #3?

6. State the basic premise upon which calibration of the eddy current system for tubing inspection is based:

7. State three conditions which require verification of calibration of the steam generator tubing eddy current examination system.

8. State the use of a Phase Angle/Defect Depth Calibration Curve.

9. Describe how to construct a Phase Angle/Defect Depth Calibration Curve.

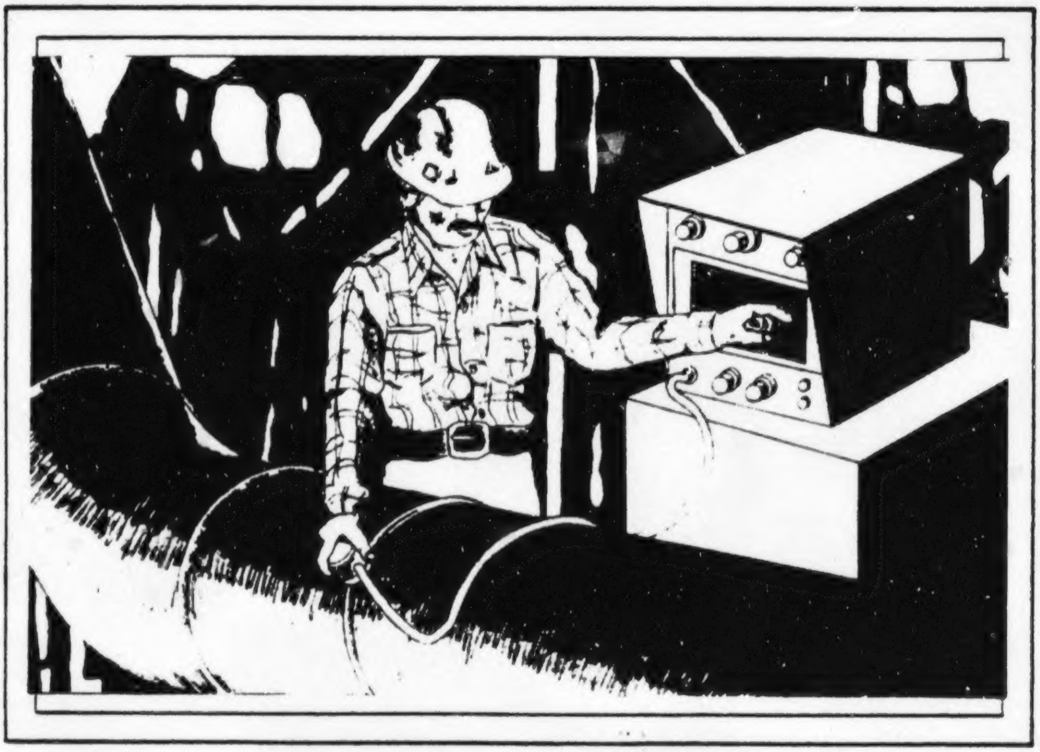
10. Describe the effect and its relative magnitude of tube supports on defect signals during eddy current examination of steam generator tubing.

11. Name three basic types of applications of eddy current testing and give one example of each.

NUCLEAR TECHNOLOGY

INDEX

COURSE 32 - NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II



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NUCLEAR TECHNOLOGY SERIES
INDEX
for
COURSE 32, NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II (SIX MODULES)

NOTE: Each module in this Course is numbered separately, and the page numbers begin with page 1 in each module. Therefore, this Index lists for each entry the module number (underlined), followed by a comma and the page number. Figures and tables are listed by their numbers, followed by the module and page number in parentheses. A Master Index is available in a separate volume. This general index merges all index entries from the 35 Nuclear Courses. It is a valuable research tool, with which the student or researcher can locate all the references to any subject within the 35 Courses.

Acoustic
  impedance, 32-1, 24; Table 32-1-5 (32-1, 25)
  velocity, 32-2, 31
American Society of Mechanical Engineers
  reference blocks, 32-2, 21
  and steam generator tube testing, 32-6, 16
American Society of Testing and Materials
  reference blocks, 32-2, 18, 19
American Welding Society
  reference blocks, 32-2, 20
Amplitude
  of wave, 32-1, 6; Fig. 32-1-1 (32-1, 9)
Attenuation
  in ultrasonics, 32-1, 29; 32-2, 32

Beam spread
  determination of, 32-3, 37
Beam spreading
  of ultrasound, 32-1, 26-28

Cables
  in magnetization, 32-3, 18, 19, 23
Circuits
  processing. See Processing circuits.
Coils
  absolute, 32-6, 11-13
  demagnetization with, 32-4, 18, 19
  inductive components of, 32-5, 12
  resistive components of, 32-5, 12
  specimen diameter and, 32-4, 17
  types of, 32-4, 16, 17
  use of, 32-4, 18
  voltage across, 32-5, 12, 13
Concrete
  ultrasonic testing of, 32-2, 33
Conductance
  and resistance, 32-5, 14
Conductivity
  in eddy current testing, 32-5, 18-20
  and International Amended Copper Standard, 32-5, 18
Conductor
  definition of, 32-5, 9, 10
Contact testing
  angle beam, and contact angle, 32-2, 5, 6; and skip distance, 32-2, 7, 8
  area-amplitude curve, 32-2, 35, 36
  distance-amplitude curve, 32-2, 36, 37
  straight beam, 32-2, 3, 4
  and surface wave technique, 32-2, 9
Couplant
  for pulse echo examination, 32-2, 17
Crest
  of wave, 32-1, 6
Curie point
  definition of, 32-3, 32
Currents
  alternating, 32-3, 12
  direct, 32-3, 11
  half-wave rectified, 32-3, 13
  in-phase, 32-5, 10
  out-of-phase, 32-5, 11

Damping block
  in transducer, 32-1, 37, 38
Demagnetization
  principles of, 32-3, 30-32
Discontinuities
  detectable, 32-4, 22-25
  finishing, 32-4, 34, 35
  inherent, 32-4, 28-30
  lap, 32-4, 31
  and magnetic materials, 32-3, 11
  processing, 32-4, 28-34
  service, 32-4, 29, 33, 34
  types of, 32-4, 28, 29
Distance-gain-size curve
  in ultrasonic testing, 32-2, 29

Eddy currents
  description of, 32-5, 14
Eddy current testing
  coat thickness measurements for, 32-6, 20-22, 29, 30
  defects in, 32-6, 10

- Eddy current testing (continued)
  - dimensions in, 32-5, 21-24
  - equipment for, 32-6, 3-5; calibration of, 32-6, 7-13
  - factors affecting, 32-5, 16-24
  - flaw detection by, 32-6, 17, 18
  - metal sorting and, 32-6, 18-20
  - of steam generator tubing, 32-6, 5, 6, 27-29
  - system for, 32-5, 15, 16
- Electromotive force
  - counter, 32-5, 8
- Energy
  - incident, 32-1, 25

- Faraday, Michael
  - and induction, 32-5, 7
- Flaws
  - detection of, 32-2, 25, 26
  - determination of position, shape, and size of, 32-2, 27-30
- Flux
  - magnetic, in a coil, 32-5, 4, 5; and current, 32-5, 5; definition of, 32-5, 3; density, 32-5, 3; and permeability, 32-5, 6
- Force
  - coercive, 32-3, 9, 30
  - magnetic, lines of, 32-5, 3; Fig. 32-5-1 (32-5, 4)
- Frequency
  - of waves, 32-1, 7

- "Head shot"
  - in magnetization, 32-3, 16
- Henry, Joseph
  - and self-induction, 32-5, 7
- Henry
  - unit of, 32-5, 7
- Hysteresis curves
  - comparison of, 32-3, 10
  - discussion of, 32-3, 8; Fig. 32-3-7 (32-3, 9)

- Immersion testing
  - bubbler technique for, 32-2, 13, 14
  - immersed technique for, 32-2, 9-11
  - squirter technique for, 32-2, 13, 14
  - water-column technique for, 32-2, 13, 14
  - wheel techniques for, 32-2, 14; Fig. 32-2-11 (32-2, 15)
- Impedance
  - definition of, 32-5, 13
- Inductance
  - definition of, 32-5, 6, 7; Eq. 32-5-2 (32-5, 8)
  - mutual, 32-5, 9
  - self, 32-5, 8
- Inductive reactance
  - definition of, 32-5, 10, 11
- Insulator
  - definition of, 32-5, 9, 10
- Interference
  - definition of, 32-1, 21
- International Amended Copper Standard
  - and conductivity, 32-5, 18
- International Institute of Welding
  - reference blocks, 32-2, 20

- Lamb waves
  - discussion of, 32-1, 11; Fig. 32-1-5 (32-1, 12)
- "Leakers"
  - definition of, 32-6, 3
- Lenz's law
  - definition of, 32-5, 8

- Magnetic
  - coupling, 32-5, 8
  - field, 32-3, 6-8
  - flux. See Flux.
  - force, lines of, 32-5, 3; Fig. 32-5-1 (32-5, 4)
- Magnets
  - discussion of, 32-3, 5-7
- Magnetically saturated
  - definition of, 32-3, 8
- Magnetic particle test
  - advantages/disadvantages of, 32-3, 34, 35
  - continuous method of, 32-4, 5
  - current and particle choice for, 32-4, 4; Fig. 32-4-1 (32-4, 5)
  - explanation of, 32-3, 7
  - magnetic field for, 32-4, 6-10
  - mediums for, application of, 32-3, 26-28; properties of, 32-3, 24-26
  - nonrelevant indications in, 32-4, 25-28
  - residual method of, 32-4, 4, 5
  - technique variables for, 32-4, 3, 4
  - ultraviolet inspection lights for, 32-3, 30; 32-4, 20, 22
  - uses for, 32-3, 32-34
  - wet method of, equipment for, 32-3, 28-30
- Magnetism
  - residual, 32-3, 9
- Magnetization
  - cable, 32-3, 18, 19, 23
  - central conductor, 32-3, 18
  - circular, 32-4, 6, 7
  - coil, 32-3, 14
  - direct induction, 32-3, 16, 17
  - "head shot" in, 32-3, 16
  - longitudinal, 32-4, 8-10
  - prod, 32-4, 10, 15, 16
  - solenoid, 32-3, 14
  - yoke, 32-3, 15-17; Fig. 32-3-16 (32-3, 18)
- Magnetizing/demagnetizing coil
  - description of, 32-3, 23
- Megahertz
  - discussion of, 32-1, 7

- Nonrelevant indications
  - in magnetic particle test, 32-4, 25-28

Oersted, Hans Christian
  and relationship between current and magnetism, 32-5, 4
Ohm's law
  definition of, 32-5, 10
Oscilloscope
  cathode ray tube in, 32-1, 41
  classes of, 32-1, 40
  deflection plates in, 32-1, 41

Penetration
  in eddy current testing, 32-5, 16, 17
Period
  of wave, 32-1, 6, 7
Permeability
  in eddy current testing, 32-5, 20, 21
  and flux, 32-5, 5, 6
Phase angle
  and coil voltage, 32-5, 13
Plastics
  ultrasonic testing of, 32-2, 33
Poles
  consequent, 32-3, 7
Porcelains
  ultrasonic testing of, 32-2, 33
Power units
  features of, 32-4, 11
  mobile, 32-4, 12
  portable, 32-3, 19; Fig. 32-3-19 (32-3, 20); Fig. 32-3-20 (32-3, 21); 32-4, 12
  stationary, 32-4, 13-15
Probe
  paint-brush, 32-2, 16, 17
Processing circuits
  discussion of, 32-5, 29
  impedance analysis, 32-5, 29-31
  modulation analysis, 32-5, 37, 38
  phase analysis, 32-5, 31-33; vector point method of, 32-5, 33, 34; ellipse method of, 32-5, 35; linear time base method of, 32-5, 36, 37
Prods
  in magnetization, 32-3, 20, 21; Fig. 32-3-21 (32-3, 22); 32-4, 15, 16
Pulse echo method. See also Contact testing; Immersion testing.
  equipment for, 32-2, 15-18

Rayleigh waves
  definition of, 32-1, 10, 11
Reference blocks
  in ultrasonic testing, 32-2, 18-21
Reflection
  and angle of incidence, 32-1, 16, 17
  from boundaries, 32-1, 23; Fig. 32-1-16 (32-1, 24)
  definition of, 32-1, 16
Refraction
  and Snell's law, 32-1, 17, 18
Resistance
  and conductance, 32-5, 14

"Right hand rule"
  for magnetic field direction, 32-3, 7; 32-5, 4

"Skin effect"
  of alternating current, 32-3, 12
Solids
  elastic bonds of, 32-1, 12, 13
Steam generator tubing
  examination, calibration for, 32-6, 7-13; equipment for, 32-6, 3-5; procedure for, 32-6, 5, 6; purpose of, 32-6, 3; records of, 32-6, 15, 16
  supports for, and eddy current testing, 32-6, 14, 15

Target
  in ultrasonic detection, 32-2, 27
Test coils
  absolute, 32-5, 26, 27
  encircling, 32-5, 25; Fig. 32-5-18 (32-5, 26)
  external comparison, 32-5, 28
  inside, 32-5, 26
  self comparison, 32-5, 27, 28
  surface, 32-5, 24, 25
Transducer
  damping block, 32-1, 38
  electrical connections to, 32-1, 39, 40
  materials for, 32-1, 36, 37
  piezoelectric effect, 32-1, 35, 36
Trough
  of wave, 32-1, 6

Ultrasonic test equipment
  A-scan pulse echo instrument as, 32-1, 30
  calibration of, 32-1, 22-24
  clock as, 32-1, 32
  controls for, 32-1, 32-35
  oscilloscope as, 32-1, 31
  probe as, 32-1, 32
  pulse generator as, 32-1, 30
  receiver-amplifier as, 32-1, 31
  transducer as, 32-1, 35, 36. See also Transducer.
Ultrasonic testing
  acoustic velocity in, 32-2, 31
  baseline in, 32-1, 41
  of concrete, 32-2, 33
  definition of, 32-1, 1
  distance-gain-size curve in, 32-2, 29
  and grain size, 32-2, 31
  lab procedure for, 32-2, 38, 39
  of plastics, 32-2, 33
  of porcelain, 32-2, 33
  uses of, 32-2, 1
Ultrasonic testing methods
  intensity, 32-1, 52-56
  intensity and transit time, 32-1, 56-57; pulse-echo type of, 32-1, 57-65, 72

Ultrasonic testing methods (continued)
  resonance frequency, 32-1, 44-52; and harmonics, 32-1, 46, 47; and oscilloscope overlay, 32-1, 49-51; problems of, 32-1, 47, 48; reading of, 32-1, 52; thickness of material by, 32-1, 44, 45; Eq. 32-1-19 (32-1, 48); 32-1, 70; Fig. 32-1-37 (32-1, 71)
  transit time, 32-1, 65, 66
Ultrasound
  definition of, 32-1, 12

Velocity
  of wave, 32-1, 7; Eq. 32-1-3 (32-1, 8)
Virgin curve
  of hysteresis curve, 32-3, 8; Fig. 32-3-7 (32-3, 9)

Wave(s)
  critical angle, 32-1, 19; Fig. 32-1-12 (32-1, 18)
  definition of, 32-1, 5
  longitudinal, 32-1, 10, 13, 14
  non-periodic, 32-1, 6
  periodic, 32-1, 6
  plate, 32-1, 11, 12
  propagation of, 32-1, 6
  shear, 32-1, 10
  standing, 32-1, 23
  surface, 32-1, 10, 11
  transverse, 32-1, 8-10; in solids, 32-1, 15
Wavelength
  definition of, 32-1, 6
Wobble
  definition of, 32-6, 9

Yokes
  magnetizing, 32-3, 23, 24
  use of, 32-4, 20